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NAVAL POSTGRADUATE SCHOOL
Monterey, California

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by

Carlos A. Wilkens A.

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On the Setting-up of an Underwater Acoustic Calibration Facility

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Submitted in partial fulfillment of the
requirements for the degree of

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I. INTRODUCTION

In a small navy with its limited resources, there is a problem in measuring the changes in the acoustic performance parameters of a sonar, such as Source Level reduction, Beam Pattern and efficiency variations, etc., due to aging, marine fouling, elements break-down. If the sonar transducer is never tested, the anomalies will not be found and the decrease in efficiency will be attributed to the signal processing stage of the sonar and/or to lack of training of the sonar operators.

Keeping this in mind, it is necessary to perform a minimum number of tests that will allow one to show the acoustical operating condition of the sonar. There are different ways that this can be done. The least accurate method is to dip a hydrophone from the ship and obtain the Source Level and the Beam Pattern. Another way is to take the transducer to a calibration site when the ship is in a dockyard and carry out all the tests required for the performance report. A better way yet is to have a calibration facility at sea where the ships can be positioned in such a way that the sonar transducer is equidistant from a circular hydrophone array, shown in Figure 1. [Ref. 19]

Out of these three possible ways, the most viable is the second. The knowledge necessary to be able to do it, from the selection of a testing site to the minimum instrumentation

required for an acoustic facility, is introduced in the following pages.

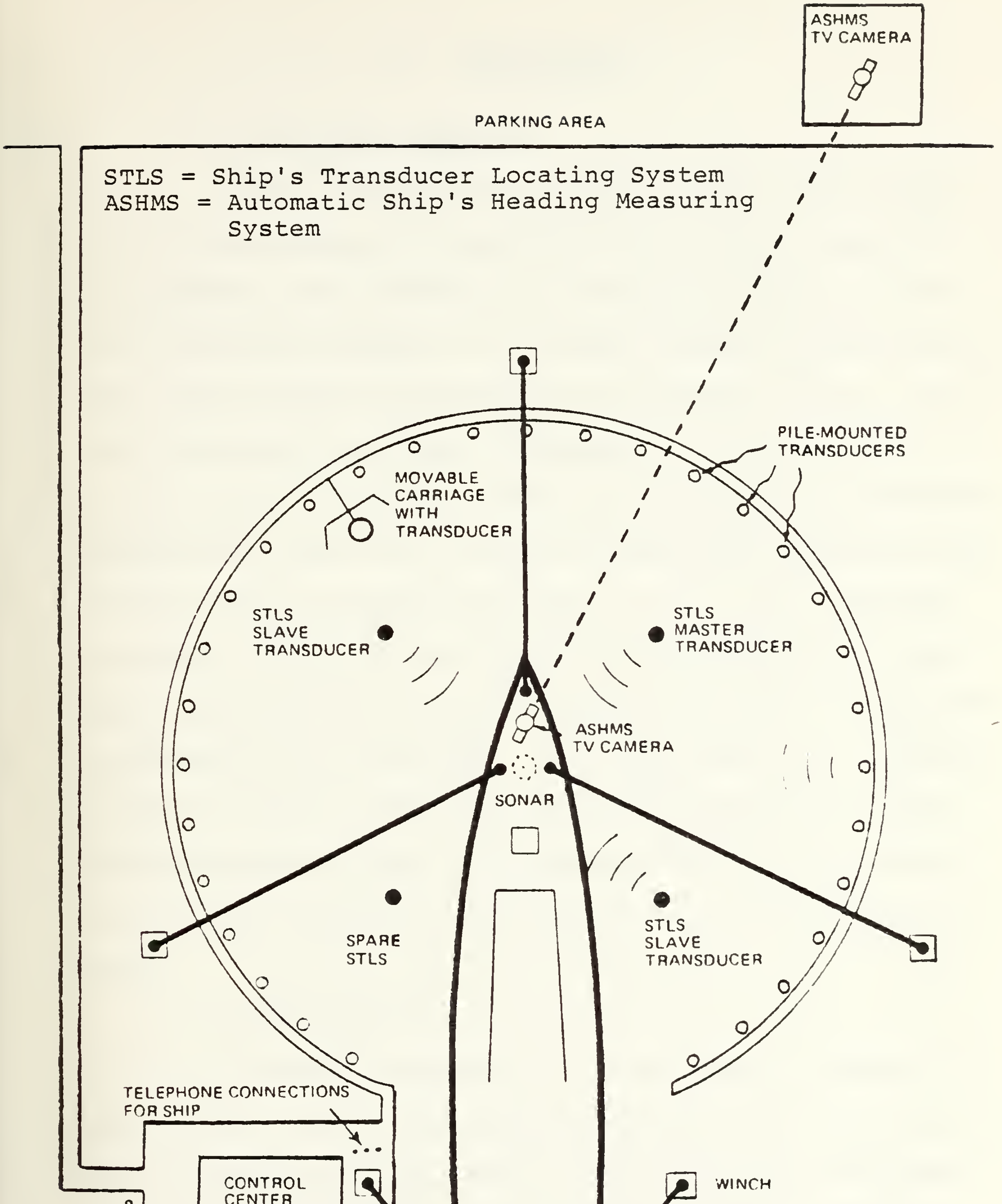


Figure 1. Calibration Site at Sea

II. CALIBRATION

1. Calibration Methods

When a calibration is taking place the parameter to be obtained usually is the free-field voltage sensitivity of a hydrophone as a function of frequency. There are two kinds of calibration methods: 1) Primary methods are those methods that require basic measurements of voltage, current, electrical and acoustical impedance, dimension of the transducers involved, medium characteristics and frequency. 2) Secondary methods are those that require a calibrated standard transducer (usually a hydrophone) that is used as a reference standard. This calibrated standard transducer must have been calibrated by a primary method. Example: comparison calibration of a hydrophone. The advantage of a secondary method is that it requires fewer measurements and hence fewer sources of errors are existent but it can never be better than a primary method when a standard hydrophone is used.

2. Definitions

Receiving response of a hydrophone is defined as the voltage across its terminals produced by a plane wave of unit acoustic pressure (before introducing the hydrophone into the sound field). It is the open-circuit response obtained when the hydrophone works into an infinite impedance.

Transmitting-current response of a projector is the pressure produced at one meter on the axis by a unit current into the projector.

Calibration of a transducer is the determination of the response as a function of frequency and direction.

Beam Pattern or Directivity Pattern response is a description of the response of the transducer as a function of direction of the transmitted or incident sound waves in a specific plane and at a specific frequency.

Transducer is a device which can transform energy from one form to another. In here the attention is directed to those transducers that transform electrical energy into acoustical energy or vice-versa.

Transformation Factor ϕ is a proportionality constant that relates the electrical output, voltage or current, with the driving force.

Source Level is a measure in decibels of the axial response of a source, measured in the far-field and extrapolated to 1 meter.

Directivity Factor R_θ is the ratio of the axial intensity of a directional source to the intensity of a spherical source, where both sources generate the same acoustical radiated power.

A. THEORY OF RECIPROCITY

The conventional reciprocity method requires no reference standard, but needs a series of measurements from several transducers. It is based on the electroacoustic reciprocity

principle, similar to the electrical reciprocity principle, for passive bilateral networks. [Ref. 2]

$$\frac{|V|}{|u|} = \pm \frac{|F|}{|I|} \qquad \frac{|V|}{|F|} = \pm \frac{|u|}{|I|} \tag{1}$$

u = velocity of the diaphragm

F = force on the diaphragm

I = absolute magnitude of the electrical current

v = applied voltage

+ = piezoelectric transducer

- = magnetostrictive transducer

The electroacoustic transducer is a device that transforms electrical power into acoustical power and vice-versa if it is reciprocal.

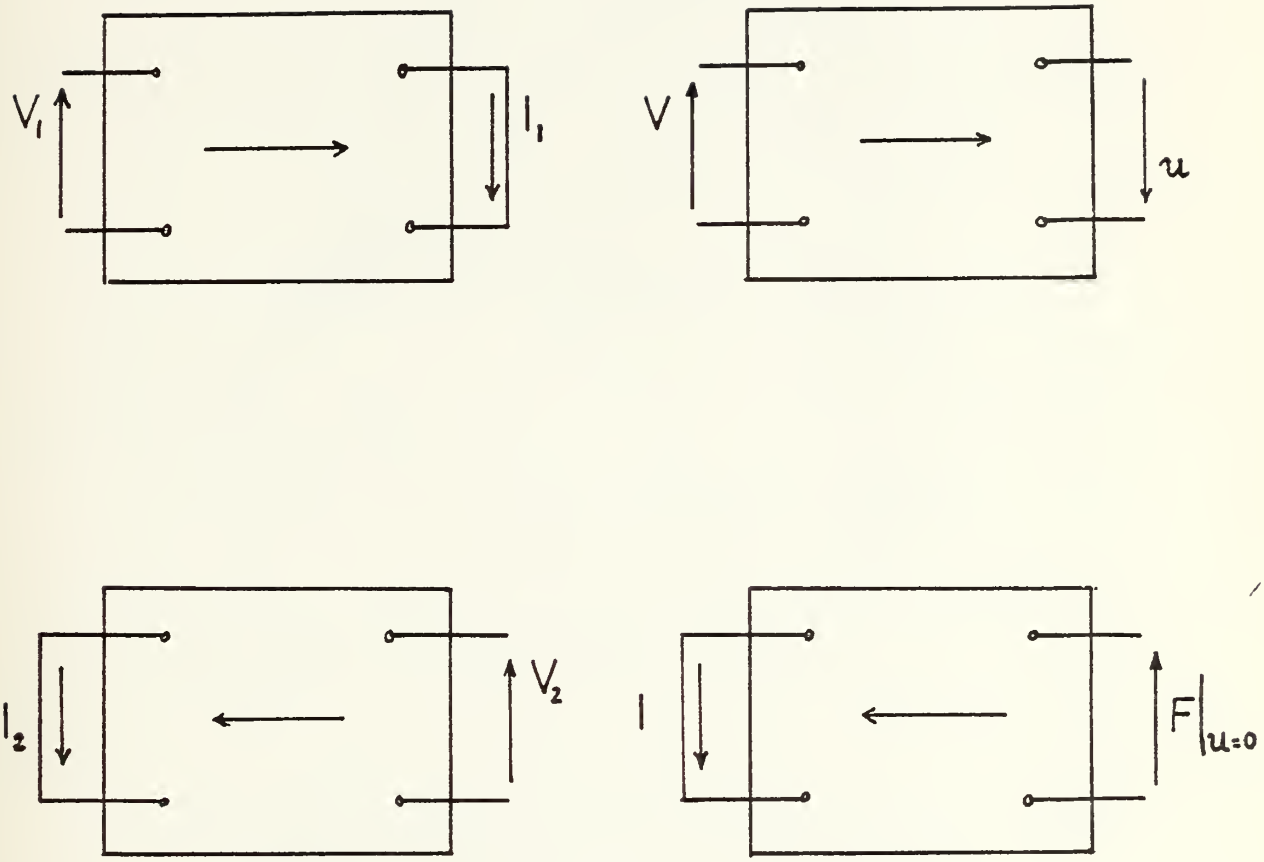
The transducer is immersed in a medium with the following characteristics: infinite, continuous and isotropic. Also it has to be considered that the medium can propagate longitudinal waves only, and therefore it can be characterized completely by its density and sound velocity.

It is assumed to be a passive transducer if all the power delivered to the electrical or acoustical system to which it is connected is derived from power absorbed from these systems by the transducer.

R is the radius vector to any point in the medium from an arbitrary origin. The surface S corresponds to the area of the face of the transducer and da is an element of area. [Ref. 6]

u(r,t) = normal velocity on the surface S

V(t) = voltage across the electrical terminals



Electrical Reciprocity   Electroacoustic Reciprocity

Figure 2. Reciprocity Principle

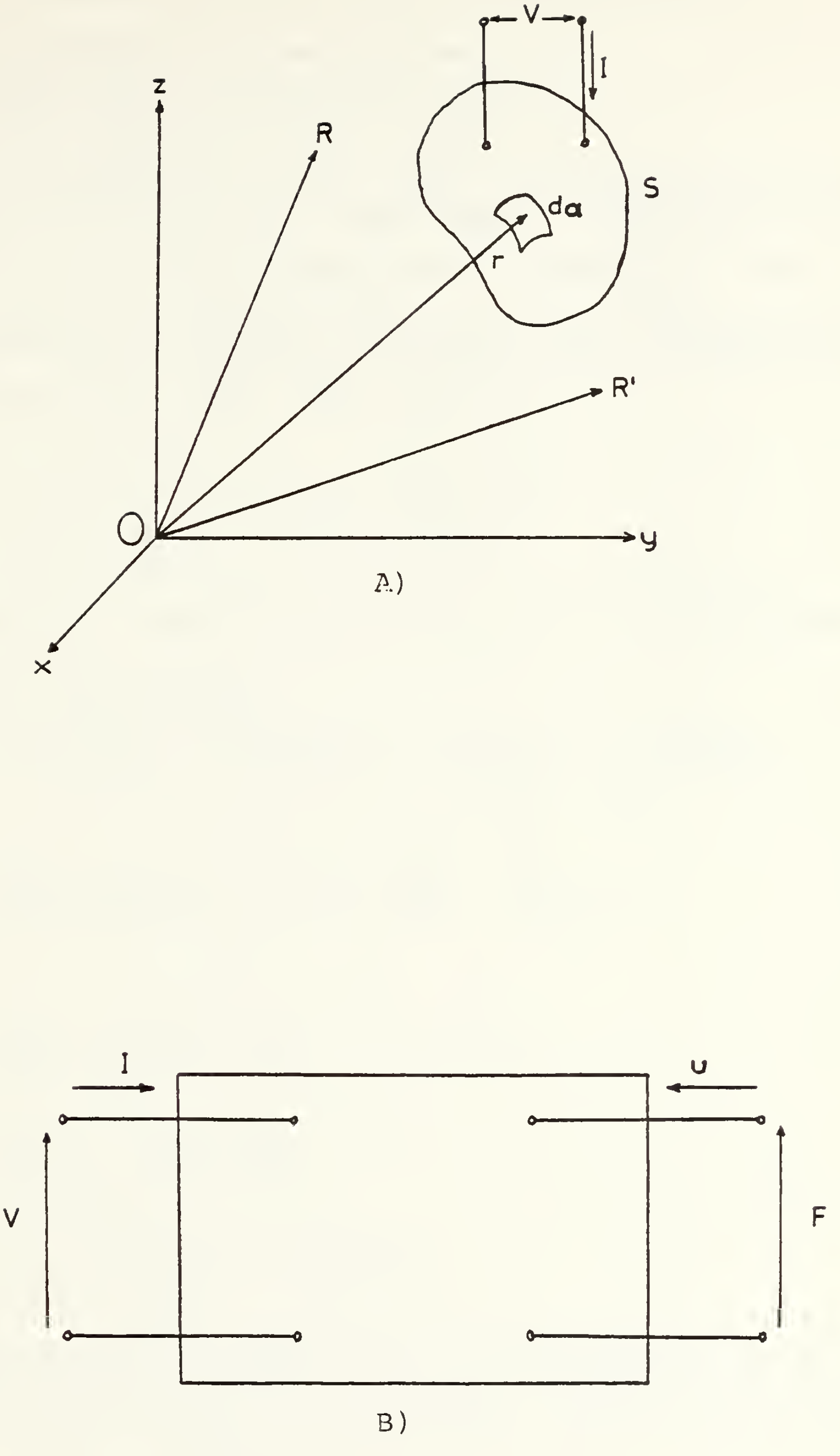


Figure 3. A) Schmatic Transducer
B) Two Port Network

I(t) = current into the terminals

p(r,t) = pressure at any point on the surface S

The following can be written:

$$p(r) = \int_S z_o(r,r')\, u(r')\, da' + h(r)\, I$$
$$V = \int_S h'(r')\, u(r')\, da' + Z_{EB}\, I \qquad (2)$$

$z_o(r,r')$, $h(r)$, $h'(r)$ and Z_{EB} are independent of $p(r)$, $u(r')$, V and I but are dependent on frequency. The normal velocity may be considered constant over the whole surface.

$$p(r) = u \int_S z_o(r,r')\, da' + h(r)\, I$$
$$V = u \int_S h'(r')\, da' + Z_{EB}\, I \qquad (3)$$

The first equation is integrated over the surface S and the force is obtained.

$$F(I,u) = u \iint z_o(r,r')\, da'\, da + I \int_S h(r')\, da'$$
$$V(I,u) = u \iint h'(r')\, da' + Z_{EB}\, I \qquad (4)$$

Define

$$T_{me} = \int_S h(r')\, da'$$
$$T_{em} = \int_S h'(r')\, da' \qquad (5)$$
$$Z_{mo} = \iint_S z_o(r,r')\, da'\, da$$

Simplifying the equations which describe the electromechanical behavior of a transducer, called the canonical equations, there is obtained:

$$F(I,u) = Z_{mo}\, u + T_{me}\, I$$
$$V(I,u) = T_{em}\, u + Z_{EB}\, I \qquad (6)$$

If one chooses that the force, F, is the analog of voltage and velocity, u, the analog of current then the equations can be represented by a two port network. (Fig. 3)

From this network some measurements can be made.

$$Z_{EB} = \left.\frac{V}{I}\right|_{u=0} \qquad \text{blocked electrical impedance}$$

$$Z_{EF} = \left.\frac{V}{I}\right|_{F=0} \qquad \text{free electrical impedance}$$

$$Z_{mo} = \left.\frac{F}{u}\right|_{I=0} \qquad \text{open circuit mechanical impedance} \tag{7}$$

$$Z_{ms} = \left.\frac{F}{u}\right|_{V=0} \qquad \text{short circuit mechanical impedance}$$

T_{em}, T_{me} are the transduction coefficients, not specified.

h(r) is the projector's 'transfer parameter' analog to the transfer impedance in electrical circuit theory.

$$h(r) = \left.\frac{p(r)}{I}\right|_{u=0} \tag{8}$$

h'(r) is also a transfer parameter and is called 'hydrophone transfer parameter.'

$z_o(r,r')$ when I = 0, gives the relationship between the pressure and normal velocity at various points on the diaphragm and is called, 'generalized open-circuit normal acoustic impedance' of the transducer surface.

When shorting the circuit, V = 0, the following is obtained:

$$\frac{u}{I} = -\frac{Z_{EB}}{T_{em}}$$

$$Z_{ms} = \frac{F}{u} = \frac{T_{me} I + Z_{mo} u}{u} = T_{me}\left(-\frac{T_{em}}{Z_{EB}}\right) + Z_{mo} \tag{9a}$$

If $$F = 0$$

$$\frac{I}{u} = -\frac{Z_{mo}}{T_{me}}$$

Introducing the last expression above

$$Z_{EF} = \left.\frac{V}{I}\right|_{F=0} = Z_{EB} - \frac{T_{em}\,T_{me}}{Z_{mo}} \tag{9b}$$

The rightmost term modifies the impedance Z_{EB} when the diaphragm is not blocked, all seen from the electrical side. When the transducer is electrically excited, the electrical impedance will change by that amount. The coupling between the mechanical and electrical energy can be described by a coupling coefficient K.

$$K^2 = \frac{T_{em}\,T_{me}}{Z_{EB}\,Z_{mo}}$$

$$Z_{EF} = Z_{EB} - \frac{T_{em}\,T_{me}}{Z_{mo}}$$

Dividing by Z_{EB}

$$\frac{Z_{EF}}{Z_{EB}} = 1 - \frac{T_{em}\,T_{me}}{Z_{mo}\,Z_{EB}}$$

Introducing equation (9a) above:

$$\frac{Z_{ms}}{Z_{mo}} = 1 - K^2 \tag{10}$$

At low frequencies, $f \rightarrow 0$, K reduces itself to the ratio of capacitances.

$$K^2_{f \rightarrow 0} = \frac{C_*}{C_0 + C_*} \tag{11}$$

Where C_o is the input capacitance and C_* is the frequency dependent capacitance of the network at low limit of frequency ($f \longrightarrow 0$). The effective coupling factor is the one at mechanical resonance.

Transmitters and Receivers: For a transmitter $F = -Zr.u$ (force is exerted on the diaphragm). (Fig. 4)

$$V = Z_{EB}\, I + T_{em}\, u$$

$$F = T_{me}\, I + Z_{mo}\, u$$

For a transmitter:

$$T_{me}\, I = -(Z_{mo} + Zr)\, u \qquad (12)$$

The sensitivity of a transmitter can be given in terms of the average pressure exerted upon the diaphragm or the pressure at one meter and on the acoustical axis of the transducer, extrapolated from the far-field.

On the diaphragm:

$$S_V^D = \left| \frac{F}{A} \frac{1}{V} \right| \qquad S_I^D = \left| \frac{F}{A} \frac{1}{I} \right| \qquad (13)$$

At one meter:

$$S_V = \left| \frac{P_{ax}(1)}{V} \right| \qquad S_I = \left| \frac{P_{ax}(1)}{I} \right| \qquad (14)$$

Using the last two equations:

$$\frac{F}{I} = \frac{T_{me}\, Zr}{Zr + Z_{mo}} \qquad (15)$$

Then

$$S_I^D = \left| \frac{Zr \quad T_{me}}{A \quad (Z_{mo} + Zr)} \right| \tag{16}$$

Combining the five last equations (12), (13), (15) and (16) one obtains:

$$S_V^D = \frac{1 \quad T_{me} \; Zr}{A \quad Z_{EB}\left(\dfrac{Z_{ms} - T_{me} I + Z_{mo} u}{u} \right)}$$

But $\quad -\dfrac{F}{u} = Zr$

$$\therefore \quad S_V^D = \left| \frac{Zr \quad T_{me} \qquad 1}{A \quad Z_{EB} \quad (Z_{ms} + Zr)} \right| \tag{17}$$

For a microphone the case is different. The force on the diaphragm will be:

$$F = \langle p_B \rangle A - Zr \cdot u \tag{18}$$

where p is the free-field pressure with no microphone present.

p_B = the pressure with the microphone present and blocked.

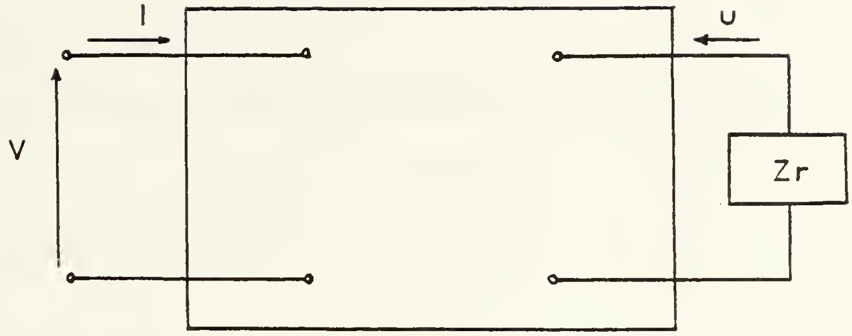
$\langle p_B \rangle$ = spatial average of p_B.

$Zr \cdot u$ = radiation force of the fluid on the diaphragm.

The pressure field is disturbed when one inserts a microphone to measure that pressure field, due to the scattering caused by the microphone itself.

Define D as the diffraction factor.

$$D = \frac{\langle p_B \rangle}{p} \tag{19}$$



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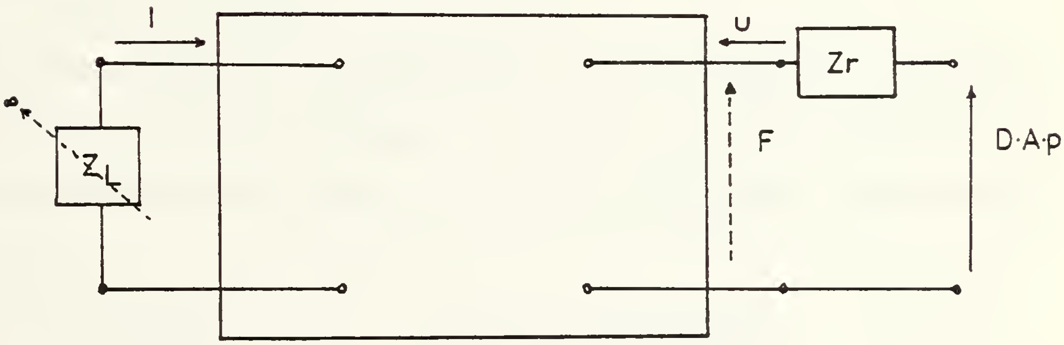


B)

Figure 4. A) Transmitter
B) Receiver

This factor may be used to measure the scattering produced by the presence of the microphone. It is dependent on the orientation of the microphone and of frequency. When lambda $\gg$ L, L being the largest dimension of the microphone, D approaches the value of unity. For a baffled piston D approaches the value of 2.

Combining the last two equations (18) and (19), one obtains

$$F = DAp - Zr\,u \qquad (20)$$

The corresponding equivalent circuit is in Figure 4b.

The importance of this circuit is that it assumes that the orientation of the microphone with respect to the pressure field, by introducing D, is known. The canonical equations for a receiver, now modified, are:

$$\begin{aligned} V &= Z_{EB}\, I + T_{em}\, u \\ DAp &= T_{me}\, I + (Z_{mo} + Zr)\, u \end{aligned} \qquad (21)$$

The response of a hydrophone can be given in two ways: 'open-circuit output voltage' or 'short-circuit current' depending whether voltage or current microphone sensitivity is wanted.

At one meter | At the diaphragm

$$M_V = \left|\frac{V}{P}\right| \quad \begin{matrix} I \to 0 \\ Z_L \to 0 \end{matrix} \qquad M_V^D = \left|\frac{V}{F/A}\right|$$

$$M_I = \left|\frac{I}{P}\right| \quad \begin{matrix} V \to 0 \\ Z_L \to 0 \end{matrix} \qquad M_I^D = \left|\frac{I}{F/A}\right| \qquad (22)$$

Combining the previous equations, it results in:

$$M_V = \left| \frac{T_{em} D A}{Z_{mo} + Zr} \right| \qquad M_V^D = \left| \frac{T_{em} A}{Z_{mo}} \right|$$

$$M_I = \left| \frac{T_{em} DA}{Z_{EB}(Z_{ms} + Zr)} \right| \qquad M_I^D = \left| \frac{T_{em} A}{Z_{EB} Z_{ms}} \right| \tag{23}$$

1. Piezoelectric Transducer

A transducer is reciprocal if $T_{em}=T_{me}$ and a transformation factor ϕ is defined as:

$$\phi = \frac{T_{em}}{Z_{EB}} \tag{24}$$

The canonical equations can be written as follows:

$$V = Z_{EB} I + Z_{EB} \phi u$$

$$\frac{F}{\phi} = Z_{EB} I + \frac{Z_{mo}}{\phi^2} \phi u \tag{25}$$

the corresponding circuit is shown in Figure 5. The coupling coefficient is now:

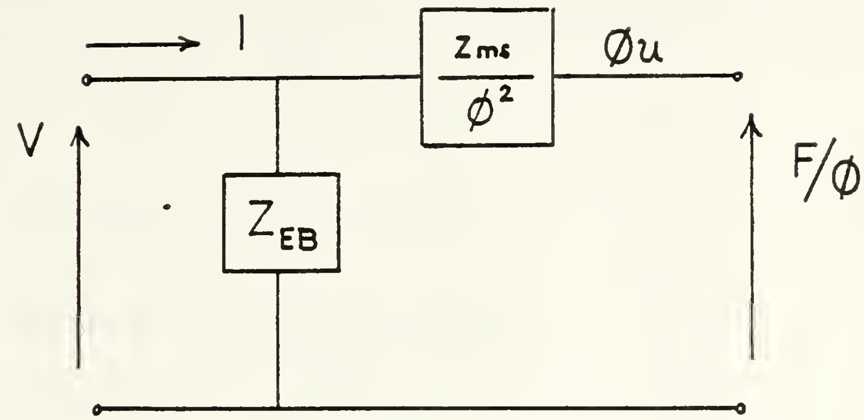
$$K^2 = \frac{Z_{EB}}{Z_{mo}/\phi^2} \tag{26}$$

replacing in equation (22), it is obtained:

$$M_V^D = \left| \frac{A K^2}{\phi} \right| \tag{27}$$

2. Magnetostrictive Transducer

This is an antireciprocal kind of a transducer and the transformation factor ϕ_M is defined as:



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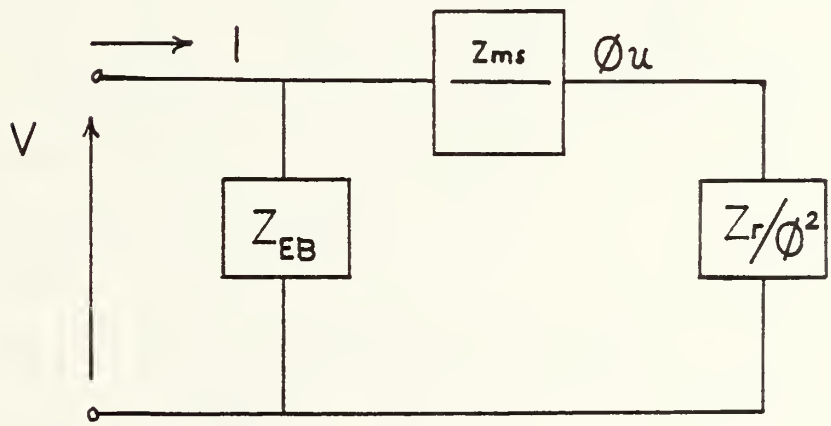


B)

Figure 5. Analog of a Piezoelectric Transducer

A) Receiver
B) Transmitter

$$\phi_M = T_{em} = -T_{me} \tag{28}$$

The canonical equations can be written as follows:

$$V = Z_{EB}\, I + \phi_M\, u$$
$$F = -\phi_M\, I + Z_{mo}\, u \tag{29}$$

Rearranging the equations,

$$V = Z_{EF}\, I + \frac{\phi_M}{Z_{mo}}\, F$$
$$u = \frac{\phi_M}{Z_{mo}}\, I + \frac{1}{Z_{mo}}\, F \tag{30}$$

a symmetric circuit, Figure 6, can be drawn from the last two, where

$$Y_{mo} = \frac{1}{Z_{mo}} = \frac{1}{R_{mo} + j(\omega m - s/\omega)} \tag{31}$$

Introducing F = Zr·u in the equation (29) above, the following relationship is obtained:

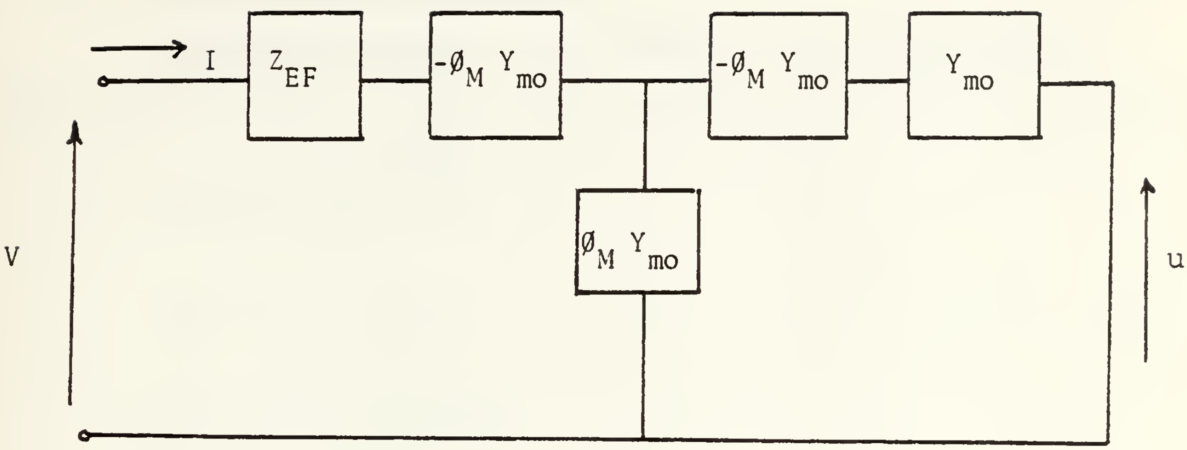
$$\phi_M\, I = (Z_{mo} + Zr)\, u \tag{32}$$

The coupling coefficient is now:

$$K^2 = -\frac{\phi_M^2}{Z_{EB}\, Z_{mo}} \tag{33}$$

The microphone sensitivity M_V^D is:

$$M_V^D = \left| \frac{K^2}{1-K^2} \cdot \frac{A}{\phi_M} \right| \tag{34}$$



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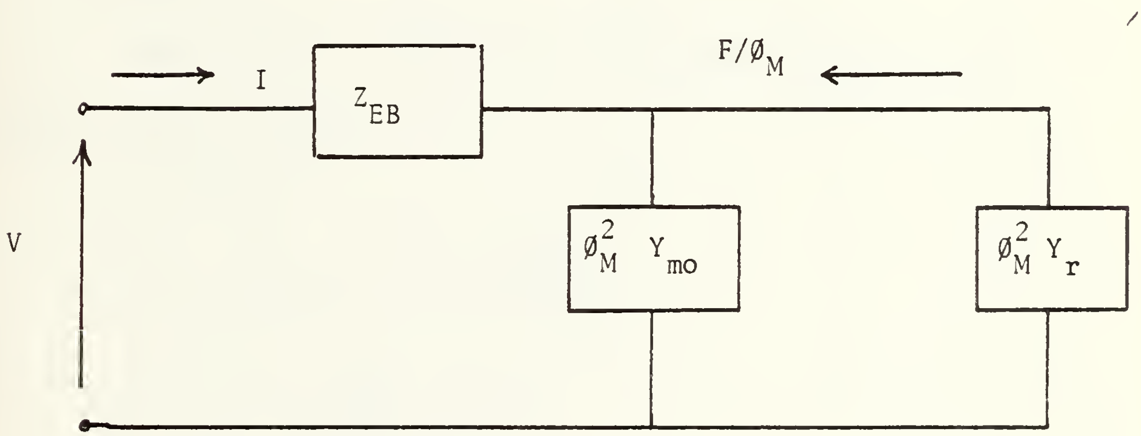


B)

Figure 6. A) Receiver
B) Transmitter

The equivalent circuit for a transmitter is shown in Figure 6 where Yr = 1/Zr.

3. Reciprocity Parameters

Spherical waves: the transducer is considered a point source and at large distances spherical waves are formed:

$$|p_r| = \frac{f \rho |Q|}{2r}$$

$$Q = u \cdot area \tag{35}$$

$$|p_r| = \frac{f \rho A |u|}{2r}$$

$|p|$ = absolute magnitude of pressure at distance r.

ρ = density

$|Q|$ = absolute magnitude of volume velocity of the source

f = frequency

The force F acting on a hydrophone due to the incident sound field is:

$$F = p_i A$$

$$\frac{V}{F} = \frac{V}{p_i A} = \frac{u}{I} = \frac{2pr}{f\rho A I}$$

$$\frac{V}{p_i} \cdot \frac{1}{A} = \frac{2r}{f\rho A} \cdot \frac{p_r}{I} \tag{36}$$

But V/p_i and p_r/I are the receiving and transmitting responses for r = 1 meter.

Define

$$M_V = \frac{V}{p_i} \qquad S_I = \frac{p_r}{I} \qquad (37$$

$$M_V = S_I \frac{2r}{f\rho} \qquad \frac{M_V}{S_I} = \frac{2r}{f\rho} = J_S$$

where J_S is the spherical wave reciprocity parameter. [Ref. 2]

Cylindrical waves: the transducer generates cylindrical waves. In this case: [Ref. 9]

$$|p_r| = \pi \rho a |u| \left(\frac{c \cdot f}{r}\right)^{1/2} \tag{38}$$

a = radius of cylinder

c = velocity of sound

Transducers behave as a hydrophone, the force exerted on it, F:

$$F = A\, p_i = 2\pi a L\, p_i \tag{39}$$

A = face area

L = length

Reciprocity relationship:

$$\frac{V}{F} = \frac{u}{I}$$

$$\frac{V}{2\pi a L p_i} = \left(\frac{r}{c \cdot f}\right)^{1/2} \frac{p_r}{\pi \rho a I}$$

$$\frac{V}{p_i} \cdot \frac{1}{2L} = \left(\frac{r}{c \cdot f}\right)^{1/2} \cdot \frac{p_r}{I \rho}$$

$$\frac{M}{S} = \left(\frac{c \cdot r}{f}\right)^{1/2} \frac{2L}{\rho c} = J_c \tag{40}$$

Plane waves: the transducer acting as a projector

$$|p_r| = \rho \cdot c \cdot |u| \tag{41}$$

As a receiver, the force exerted upon it is

$$F = 2 A p_i \tag{42}$$

The factor 2 comes from pressure doubling at the transducer's face

$$\frac{V}{F} = \frac{u}{I}$$

$$\frac{V}{2A p_i} = \frac{p_r}{I \rho c}$$

$$\frac{V}{p_i} \cdot \frac{1}{2A} = \frac{1}{\rho c} \cdot \frac{p_r}{I}$$

$$\frac{M}{S} = \frac{2A}{\rho c} = J_p \tag{43}$$

The three reciprocity parameters can be written:

Plane: $$J_p = \frac{2}{\rho c} (\lambda r)^0 A \tag{44}$$

Cylindrical: $$J_C = \frac{2}{\rho c} (\lambda r)^{1/2} L \tag{45}$$

Spherical: $$J_S = \frac{2}{\rho c} (\lambda r)^1 \tag{46}$$

The exponent of (λr) indicates the way in which the waves spread.

B. CONVENTIONAL RECIPROCITY

1. Description

Electroacoustic or conventional or three-transducer spherical wave reciprocity has the characteristic that it does not need any reference transducer for which the frequency response is known. It requires that one of the transducers be reciprocal, the second has to be a projector and the third, a hydrophone. Knowing the frequency response of the second and third would be helpful and the calibrated instrument need not to be reciprocal. The formula of calibration is derived for the free-field voltage sensitivity M_H of the hydrophone. [Refs. 1 and 2]

The three transducers can be placed at equal distances r to each other, Figure 7.

First step: the projector P is driven with a known current i and the responses (voltage v) of T and H are recorded (output terminals).

Second step: now T is driven with the same current i and the voltage v_H' of H is recorded.

$$\frac{M_H}{M_T} = \frac{v_H}{v_T} \tag{47}$$

M_T is the unknown receiving response of T. It is assumed that spherical radiation is taking place. The transmitting response of the projector is:

$$S_P = \frac{p_r \cdot r}{i} \qquad \text{at distance } r \tag{48}$$

$$M_H = \frac{v_H}{p_i} \tag{49}$$

Multiplying

$$S_P \cdot M_H = \frac{v_H \cdot r}{i} \qquad \frac{S_P}{S_T} = \frac{v_H}{v_H'} \qquad S_P = \frac{S_T\, v_H}{v_H'} \tag{50}$$

From

$$M_H = \frac{M_T\, v_H}{v_T}$$

$$S_P M_H = \frac{S_T\, v_H}{v_H'} \cdot \frac{M_T\, v_H}{v_T} = \frac{v_H\, r}{i}$$

$$S_T M_T = \frac{v_H'\, v_T}{v_H} \tag{51}$$

By reciprocity

$$S_T = \frac{M_T}{J_S}$$

$$M_T^2 = J_S\, \frac{v_H'\, v_T}{v_H} \cdot \frac{r}{i}$$

$$M_T = J_S \left(\frac{v_T\, v_H'}{v_H} \cdot \frac{r}{i} \right)^{1/2} \tag{52}$$

$$M_H = \frac{M_T\, v_H}{v_T} = J_S \left(\frac{v_H\, v_H'}{v_T} \cdot \frac{r}{i} \right)^{1/2} \tag{53}$$

J_s is independent of the type or construction details of the transducer. The reciprocal transducer is the one that is linear, passive and reversible.

2. <u>Reciprocity Check</u>

Using two reversible transducers T_1 and T_2, take T_1 and drive it with current i_1 and measure the open circuit voltage v_2 at T_2. Then, drive T_2 with i_2 and measure v_1. If both are reversible, the following relation should be obtained.

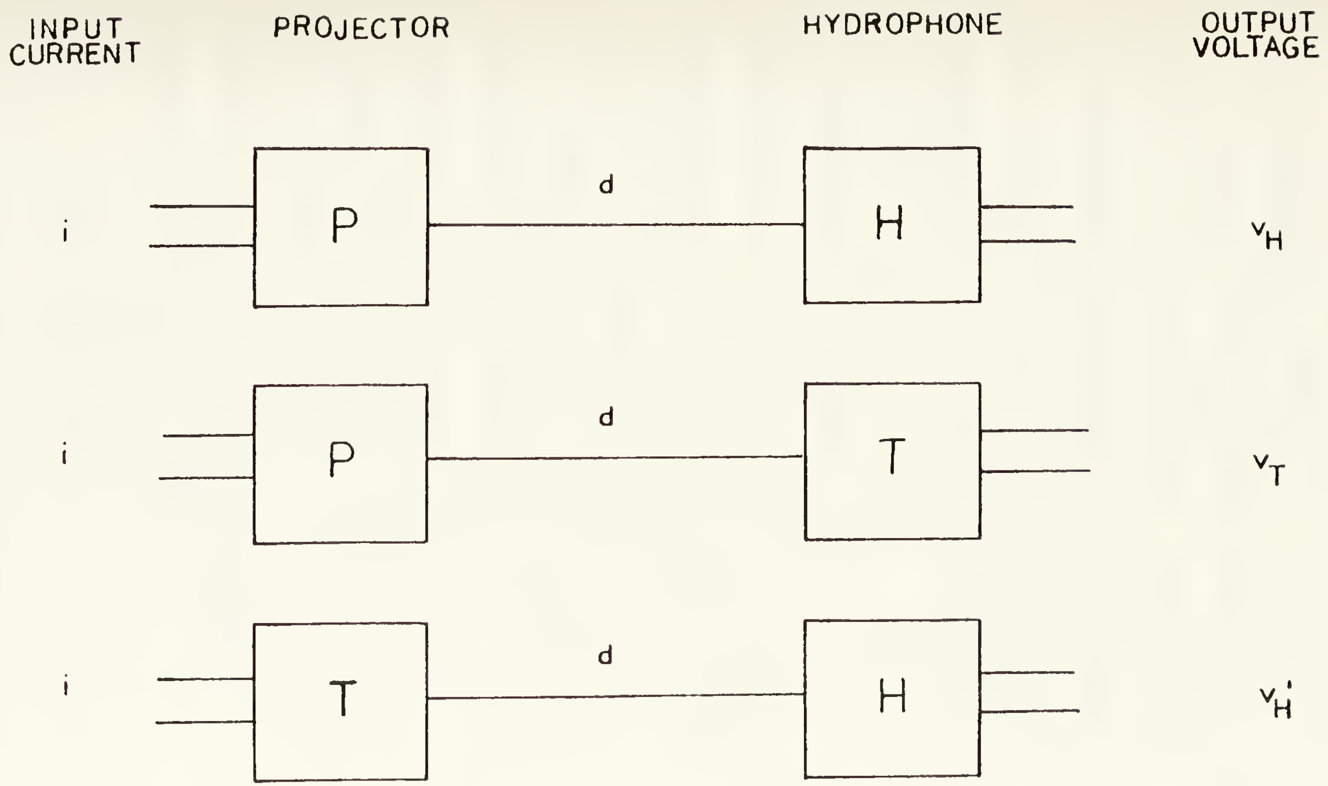


Figure 7. Conventional Method Transducer Arrangement

$$\frac{V_2}{i_1} = \frac{V_1}{i_2} \tag{54}$$

It is recommended that both transducers be dissimilar because they could be non-linear at the same point. [Ref. 1]

C. COMPARISON METHOD

A sound field is generated by a projector whose characteristics are unimportant. This method consists of exposing a calibrated hydrophone and the unknown hydrophone to the same pressure field. This is achieved by immersing the two hydrophones in the exactly same place and at a distance from the projector where the fact, that plane waves reach the hydrophones, is assured. If any of the hydrophones are directional, their acoustical axis should be pointing toward the projector. The open-circuit output voltage V_{H_S} of the standard hydrophone is measured when the projector is driven with a known current. The standard hydrophone is then substituted by the unknown one and its open-circuit output voltage V_{H_X} is measured while the projector's driving current has been kept constant. (Fig. 8) Each measurement must be done for each frequency. If the standard hydrophone's voltage sensitivity is M_S then the unknown is obtained from the following relationship: [Ref. 1]

$$M_X = \frac{v_{H_X}}{v_{H_S}} M_S \tag{55}$$

The possible error sources for this method are:

1) Not having a true open-circuit voltage measurement.

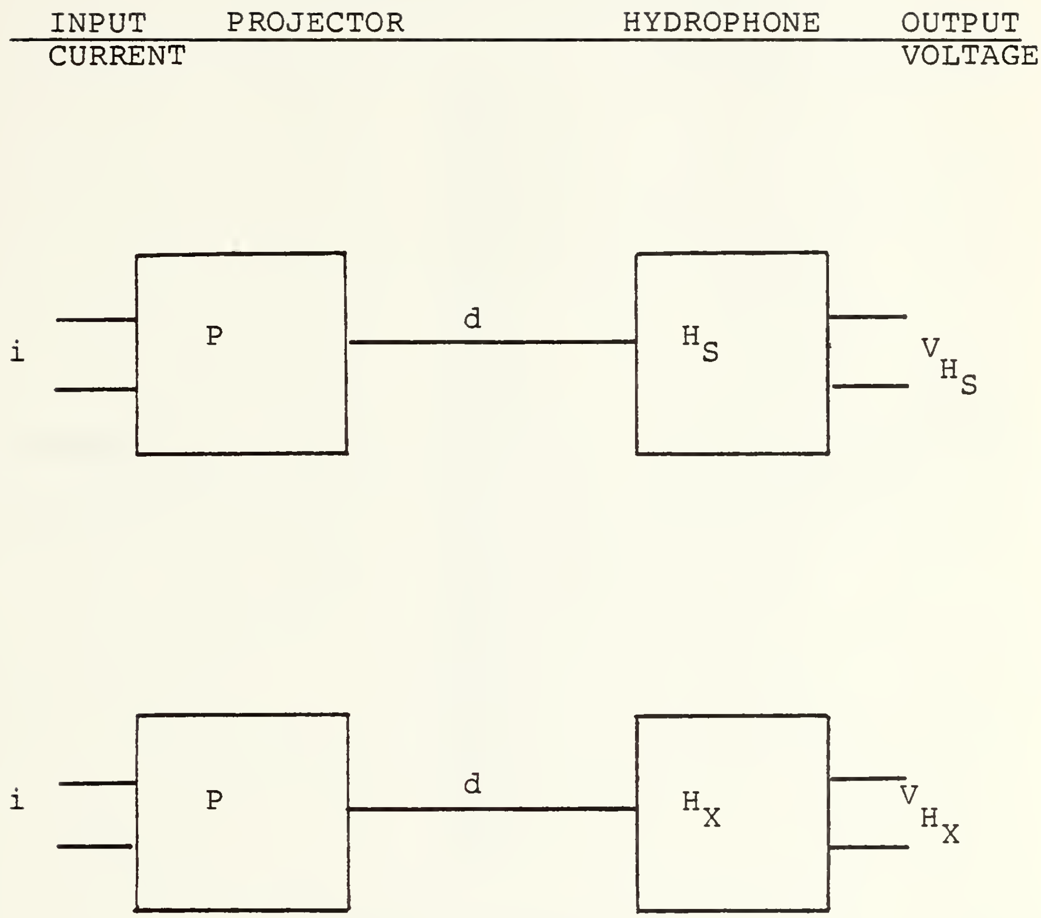
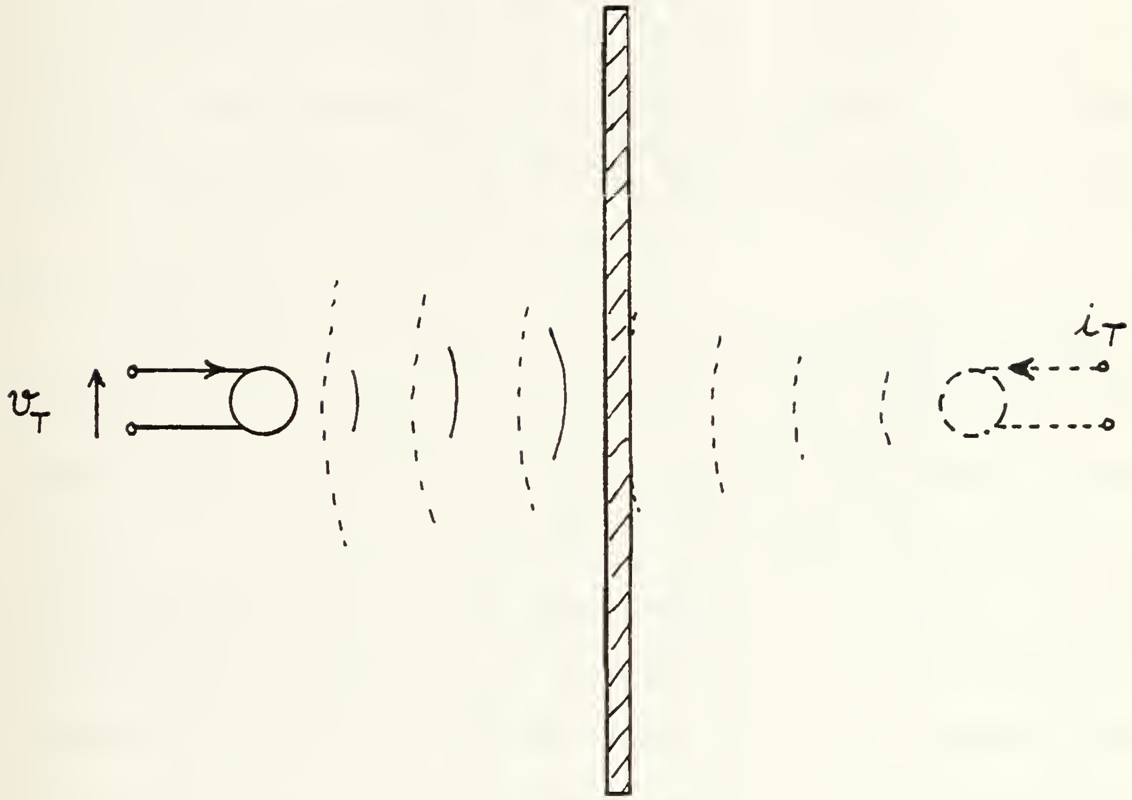


Figure 8. Comparison Method Transducer Arrangement



Rigid Boundary

Figure 9. Self Reciprocity Transducer Arrangement

2) Too much noise.

3) Absence of free-field.

4) Instability of the calibrated hydrophone.

When this method is carried on in a small tank precautions have to be taken such that the following requirements for a valid free-field voltage sensitivity calibration are fulfilled:

$$L \ll \lambda \quad , \quad Z_r \ll Z = \frac{F}{u} \quad \text{(from Fig. 4b)} \qquad (56)$$

The last requirement is difficult to achieve at resonance, hence, this method is valid for small nonresonant hydrophones.

D. SELF RECIPROCITY

This method is done by reflecting the signal from a perfectly reflecting boundary back to the reciprocal transducer so that it receives its own signal as shown in the figure. In practice the interface air-water is used as a non-rigid boundary. The image source is thought to be the second transducer with the transmitting current response identical to the real transducer. Using the pulsed-sound technique, the driving current i and the received open circuit voltage v_T are measured. The free-field voltage sensitivity M_T is calculated from the following relationship. [Refs. 1 and 7]

$$M_T = \left(\frac{v_T}{i_T} J\right)^{1/2} \qquad (57)$$

E. DIRECTIVITY FACTOR AND DIRECTIVITY INDEX

The Directivity Factor R_θ or Directivity Index DI characterizes the far-field directionality of a transducer.

The Directivity Factor can be expressed as:

$$R_\theta = \frac{4\pi r^2 (p_a)^2}{\int_S p^2(\theta,\emptyset)\, dS} \tag{58a}$$

$$R_\theta = \frac{4\pi}{\int_0^{2\pi}\int_0^{\pi}\left[\frac{p(\theta,\emptyset)}{p_a}\right]^2 \sin\theta\, d\theta\, d\emptyset} \tag{58b}$$

where

$p(\theta,\emptyset)$ = sound pressure as a function of direction at some fixed distance.

p_a = sound pressure in the reference direction at the same distance.

r = radius of a sphere whose center is the effective acoustic center of the source.

dS = area differential of the sphere.

The calculation of R_θ using the aforementioned equation can be carried out only for some ideal cases. [Ref. 4]

The Directivity Index is defined to be:

$$DI = 10 \log_{10} R_\theta = 10 \log_{10} \frac{I(\theta,\emptyset)}{I_a} \quad \text{[averaged over all directions]} \tag{59}$$

There are cases for which a DI can be obtained in a relatively simple manner. One way to do it is the following. From a polar beam pattern plot obtain at all angles the difference in decibels between the main beam and other points. For each case find the angle θ. These data should be plotted in a rectangular plot. On the ordinates the ratio Iav/I_a sine θ and on the abscissa the angle in radians. If one measures the area under the curve and multiplies it by the

scales chosen for the abscissa and ordinate (if they were scaled), one should obtain:

$$R_\theta = \int_0^\pi \frac{I_{av}}{I_a} \sin\theta \, d\theta \tag{60}$$

But the method mentioned before is tedious and to facilitate the calculations a chart is used. Very often it is desired to determine the Directivity Factor of a circular piston transducer from experimental data. The Directivity Factor for that transducer is:

$$R_\theta = \frac{4\pi r^2 p_a^2}{\int_0^\pi 2\pi r^2 p^2(\theta) \sin\theta \, d\theta} \tag{61}$$

$p(\theta)$ = sound pressure at distance r where spherical divergence exists.

p_a = maximum sound pressure at the distance r in the reference direction, in this case parallel to the axis of symmetry.

θ = angle between the axis of symmetry and the direction of the sound ray.

The area of the spherical segment is proportional to

$$\int_0^\theta \sin\theta \, d\theta = 1 - \cos\theta \tag{62}$$

If the pressure squared is plotted along the vertical axis and the area of the spherical sector along the horizontal axis, the equation for R_θ may be evaluated with a planimeter. [Ref. 5]

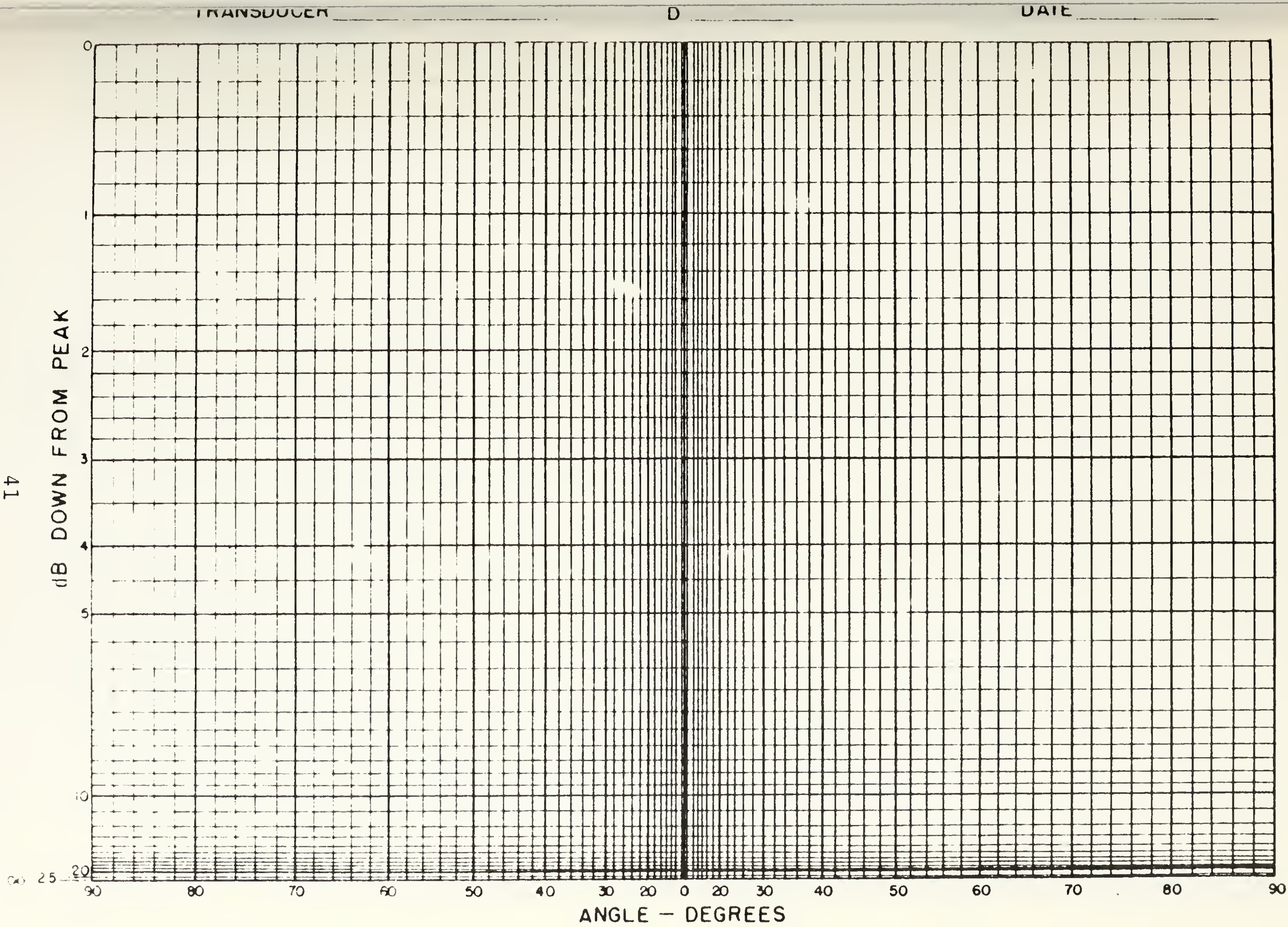


Figure 10. Chart 1 for Calculating Directivity Factor

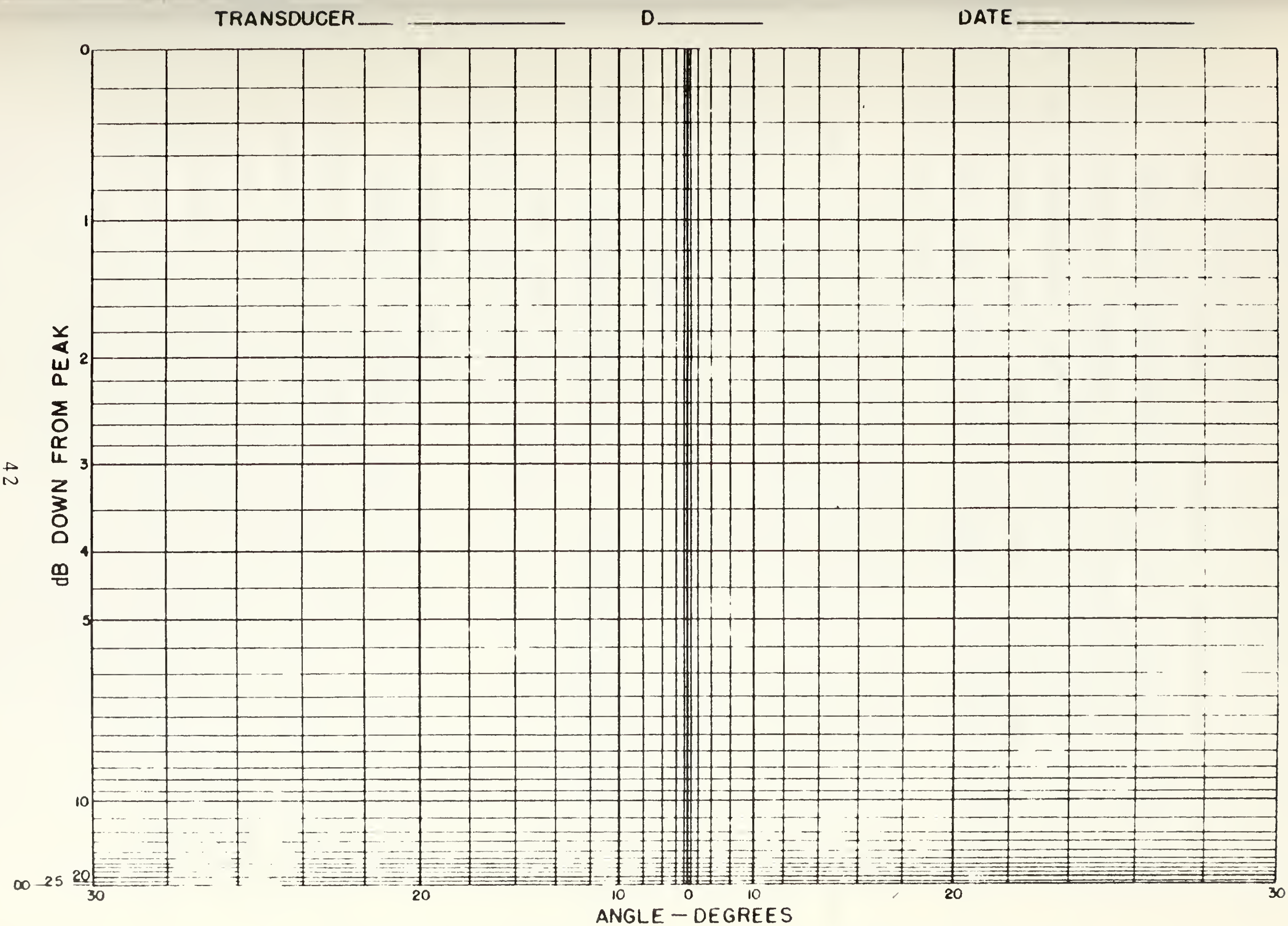


Figure 11. Chart 2 for Calculating Directivity Factor

In chart 1 (Fig. 10) the scale of sound pressure level in decibels is distorted to give a pressure-squared plot and the area of the spherical segment is expressed in terms of θ. The chart is prepared from 0 to 90 degrees on each side of the axis of symmetry. It is necessary to plot front and back hemispheres separately and find the total area under the two curves. The Directivity Factor is then obtained by dividing twice the area of the chart by the total area under the two curves.

For a circular piston with a very sharp pattern there is chart 2, Fig. 11, that covers 30 degrees on each side of the axis of symmetry. The effective area of this chart for one hemisphere is:

$$\frac{1}{1 - \cos 30^\circ} = 7.46 \tag{63}$$

$$R_\theta = \frac{2 \cdot \text{area of chart 1}}{\text{area under the curve}} = \frac{14.9 \cdot \text{area of chart 2}}{\text{area under the curve}} \tag{64}$$

These charts can be used for any pattern having a circular symmetry about an axis.

F. IMPEDANCE METHOD

Impedance is useful because it gives information for impedance matching between the transducer and the electronic transmitting or receiving equipment, it is used for the calculation of computing efficiency and is a way to analyze the performance of the transducer. Although it is measured electrically it is a function of mechanical mass as well as the acoustical characteristics of the hydrophone.

When carrying out impedance measurements the transducer should be loaded as it is done in practice, usually a free-field load, and free of boundary interference. It is important that the transducer is properly grounded and that the cable be the shortest possible so that the effects of capacitance and inductance of the cable do not affect the impedance reading, especially at high frequency. [Refs. 1 and 8]

1. Piezoelectric Transducer

From before, the equations

$$V = Z_{EB} I + Z_{EB} \phi u$$
$$\frac{F}{\phi} = Z_{EB} I + \frac{Z_{mo}}{\phi^2} \phi u \tag{65}$$

that describe a reciprocal transducer and which can be represented by the network shown in Figure 12 and where the maximum velocity u is obtained when Z_{ms}+Zr is minimized for constant ϕ. The admittance of the circuit as a transmitter is:

$$Y_E = \frac{1}{Z_{EB}} + \frac{\phi^2}{Zr + Z_{ms}} = Y_{EB} + Y_{MOT}$$
$$Y_{EB} = G_{EB} + j B_{EB}$$
$$Y_{MOT} = G_{MOT} + j B_{MOT} \tag{66}$$
$$Y_E = (G_{EB} + G_{MOT}) + j(B_{EB} + B_{MOT})$$

The transmitting transducer can be represented by the circuit shown in Figure 5b where

$$Y_{EB} = G_{EB} + j B_{EB} = \frac{1}{R_0} + j \omega C_0 \tag{67}$$

is equal to the input admittance. R_o and C_o are the input resistance and capacitance of the circuit, respectively. Define R_m as the mechanical resistance coming from frictional and viscous mechanism where the mechanical energy transforms into heat.

$$Z_{mo} = R_m + j\left(\omega m - s/\omega\right) \tag{68}$$

$$G_{MOT} = \frac{(R_m + Rr)\,\phi^2}{(R_m + Rr)^2 + (\omega m - s/\omega + Xr)^2} \tag{69}$$

$$B_{MOT} = -\frac{(\omega m - s/\omega + Xr)\,\phi^2}{(R_m + Rr)^2 + (\omega m - s/\omega + Xr)^2} \tag{70}$$

If it is assumed that $Xr \approx 0$ and R_m, R_r, m and s are constants, then G_{MOT} vs. B_{MOT} is a circumference. If it is defined:

$$\begin{aligned} a &= \phi^2 \\ b &= R_m + Rr \\ d &= \omega m - s/\omega + Xr \end{aligned} \tag{71}$$

then it results in:

$$G_{MOT} = \frac{a\,b}{b^2 + d^2} \qquad B_{MOT} = -\frac{a\,d}{b^2 + d^2} \tag{72}$$

By combining the equations, the circumference equation is obtained (Fig. 12):

$$B_{MOT}^2 + \left(G_{MOT} - \frac{1}{2}\,\frac{a}{b}\right)^2 = \frac{1}{4}\left(\frac{a}{b}\right)^2 \tag{73}$$

radius: $\frac{1}{2}\,\frac{a}{b}$

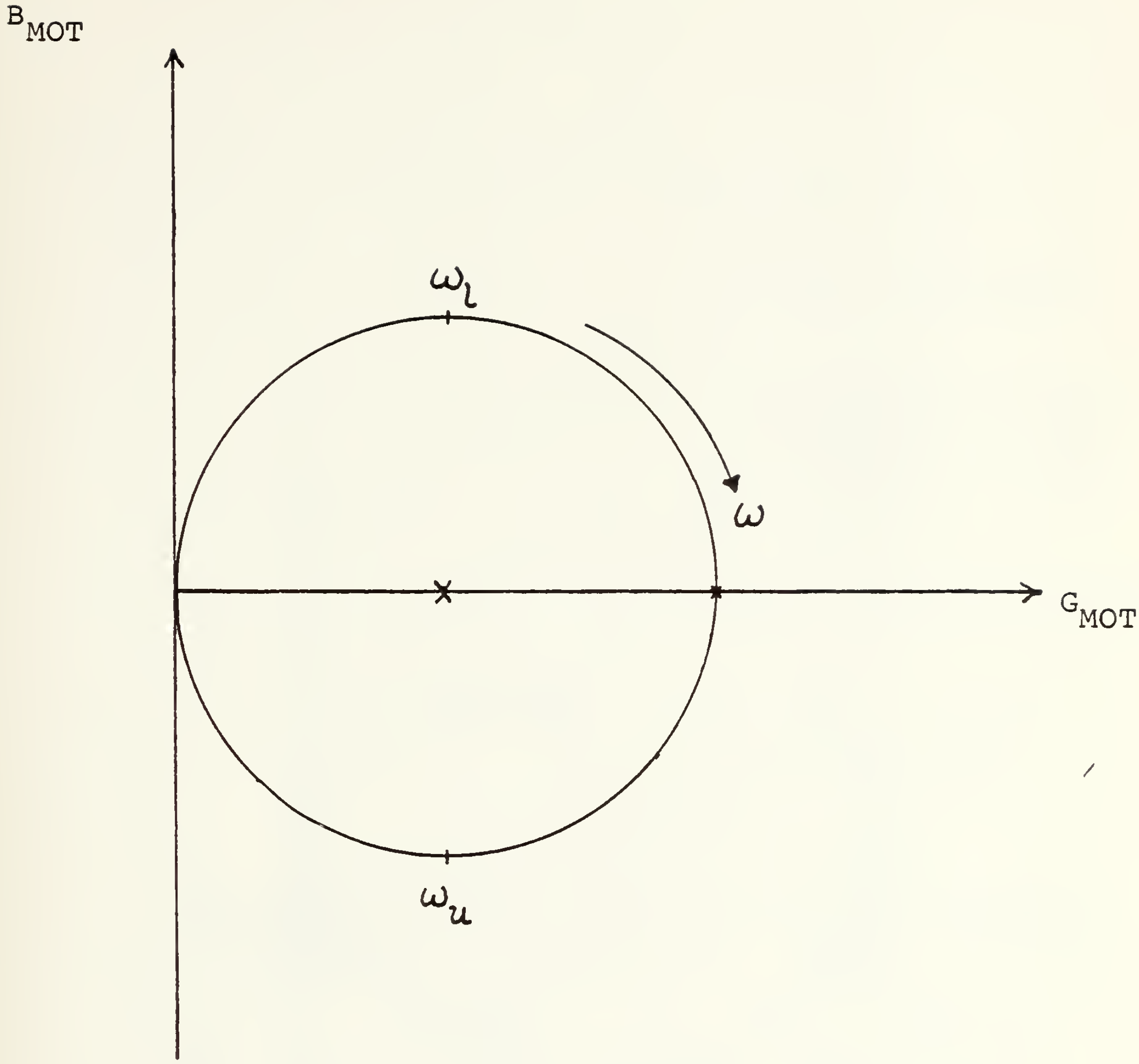


Figure 12. Motional Admittance Plot

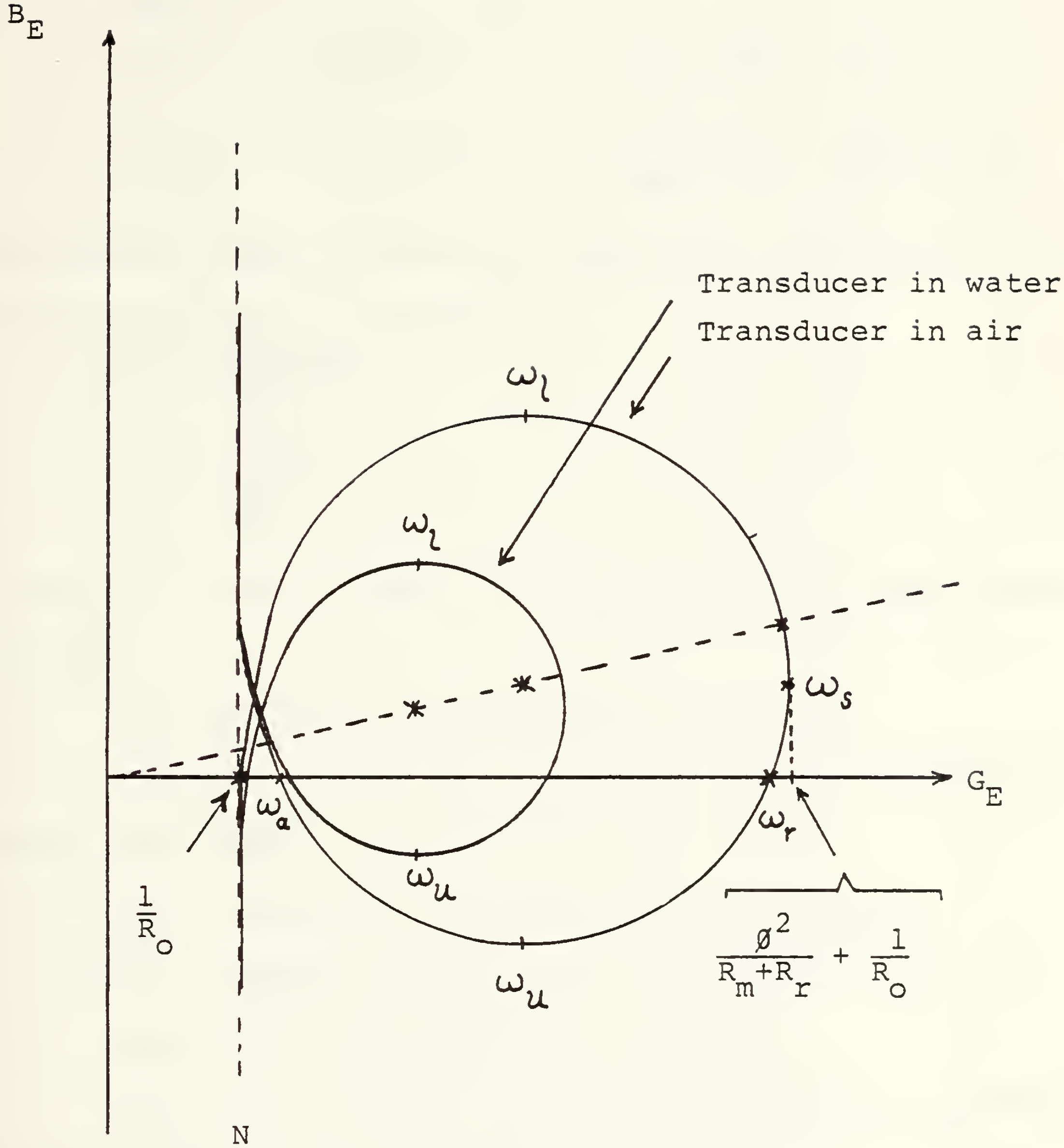


Figure 13. Complex Admittance Plot

center at: $\frac{1}{2}ab = G$

$$\text{diameter: } \frac{\phi^2}{R_m + R_r} \tag{74}$$

when

$d = 0 \qquad \omega = \omega_s \qquad G_{MOT} = \frac{a}{b} \qquad B_{MOT} = 0$

$d = \pm b \qquad \omega = \omega_l \text{ and } \omega_u \qquad G_{MOT} = \frac{1}{2}\frac{a}{b} \qquad B_{MOT} = \pm\frac{1}{2}\frac{a}{b}$

The measured complex admittance according to equation (66) is plotted in Figure 13. Define:

$$R = \frac{R_m + R_r}{\phi^2}$$
$$L = m/\phi^2 \tag{75}$$
$$C = \phi^2/s$$

An analog of the transducer can be drawn using these parameters. (Fig. 14b)

ω_s = frequency of mechanical resonance

ω_u, ω_l are upper and lower half power frequencies for the motional branch.

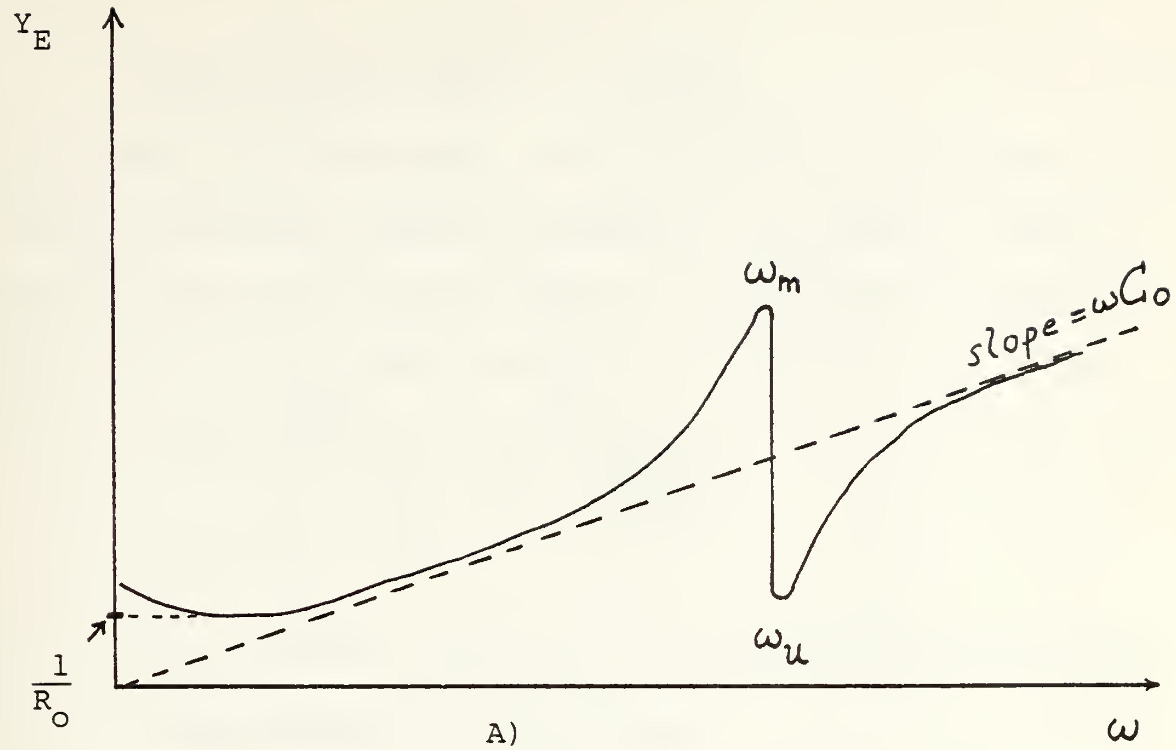
ω_m = frequency of maximum input admittance

ω_n = frequency of minimum input admittance

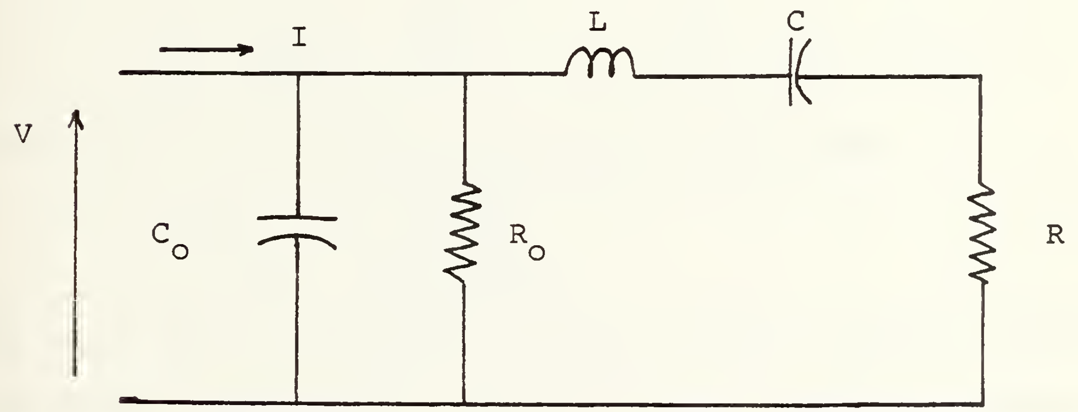
ω_r = electrical resonance frequency

ω_a = electrical antiresonance frequency (vanishing susceptance and minimum conductance).

If the circuit is small it may not have electrical resonance. From the analog of the transducer its quality factor may be deduced.



A)



B)

Figure 14. A) Admittance Versus Frequency
B) Electrical Analog of a Piezoelectric Transducer

$$Q = \frac{\omega_s}{\omega_u - \omega_l} = \frac{\omega_s L}{R} = \frac{\omega_s m}{Rr + R_m} \qquad (76)$$

Also, the electroacoustic efficiency can be calculated from the data obtained from the impedance measurement. Electro-acoustic efficiency is the ratio of the acoustic power radiated to the total power consumed at mechanical resonance.

$$\eta = \frac{Rr}{Rr + R_m} \cdot \frac{R_o}{R_o + \frac{Rr + R_m}{\phi^2}} \qquad (77)$$

$$\eta = \eta_{MA} \cdot \eta_{EM}$$

$\eta =$ mechano acoustical $\cdot$ electro mechano efficiency

2. Magnetostrictive Transducer

The canonical equations of this kind of transducer are, as derived before:

$$F = -\phi_M I + Z_{mo} u$$

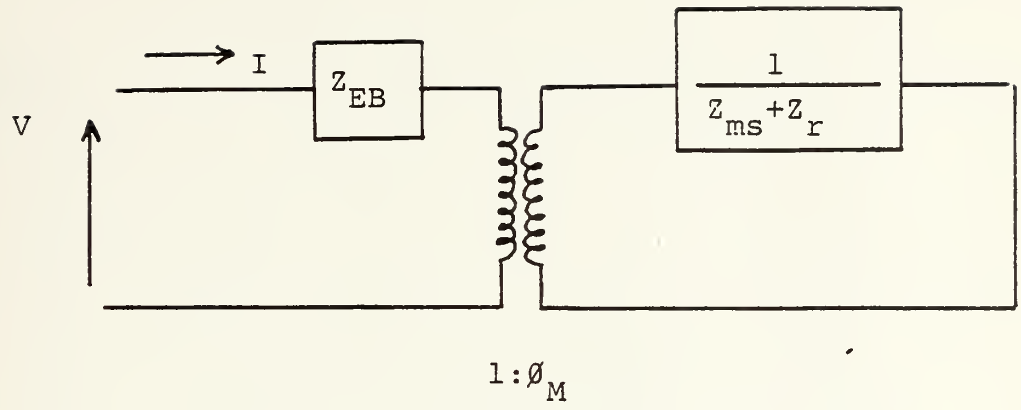
$$V = Z_{EB} I + \phi_M u \qquad (78)$$

from which the following expression is derived.

$$Z = Z_{EB} + \frac{\phi_M^2}{Z_{mo} + Zr} \qquad (79)$$

The equivalent circuits for this magnetic coupled transducer are shown in Figure 15. If the complex impedance measured points are plotted, the following graph is obtained, shown in Figure 16.

$$\text{diameter:} \ \frac{\phi_M}{R_{mo} + Rr} \qquad (80)$$



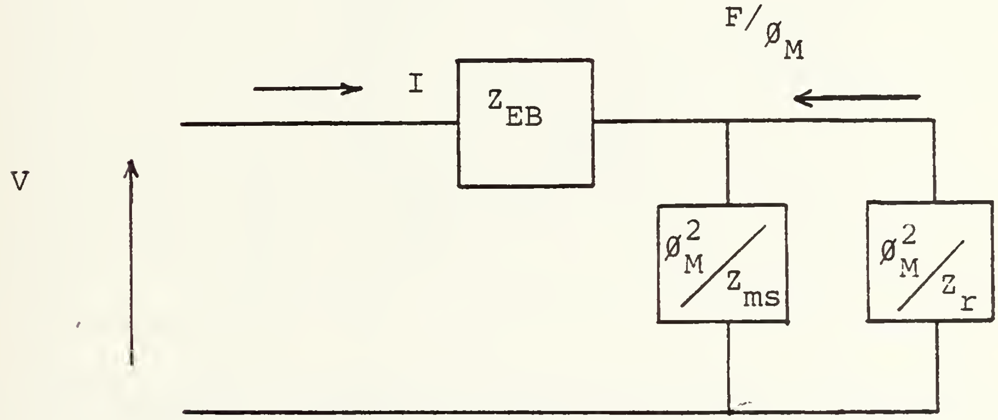


Figure 15. Analog of a Magnetic Coupled Transducer

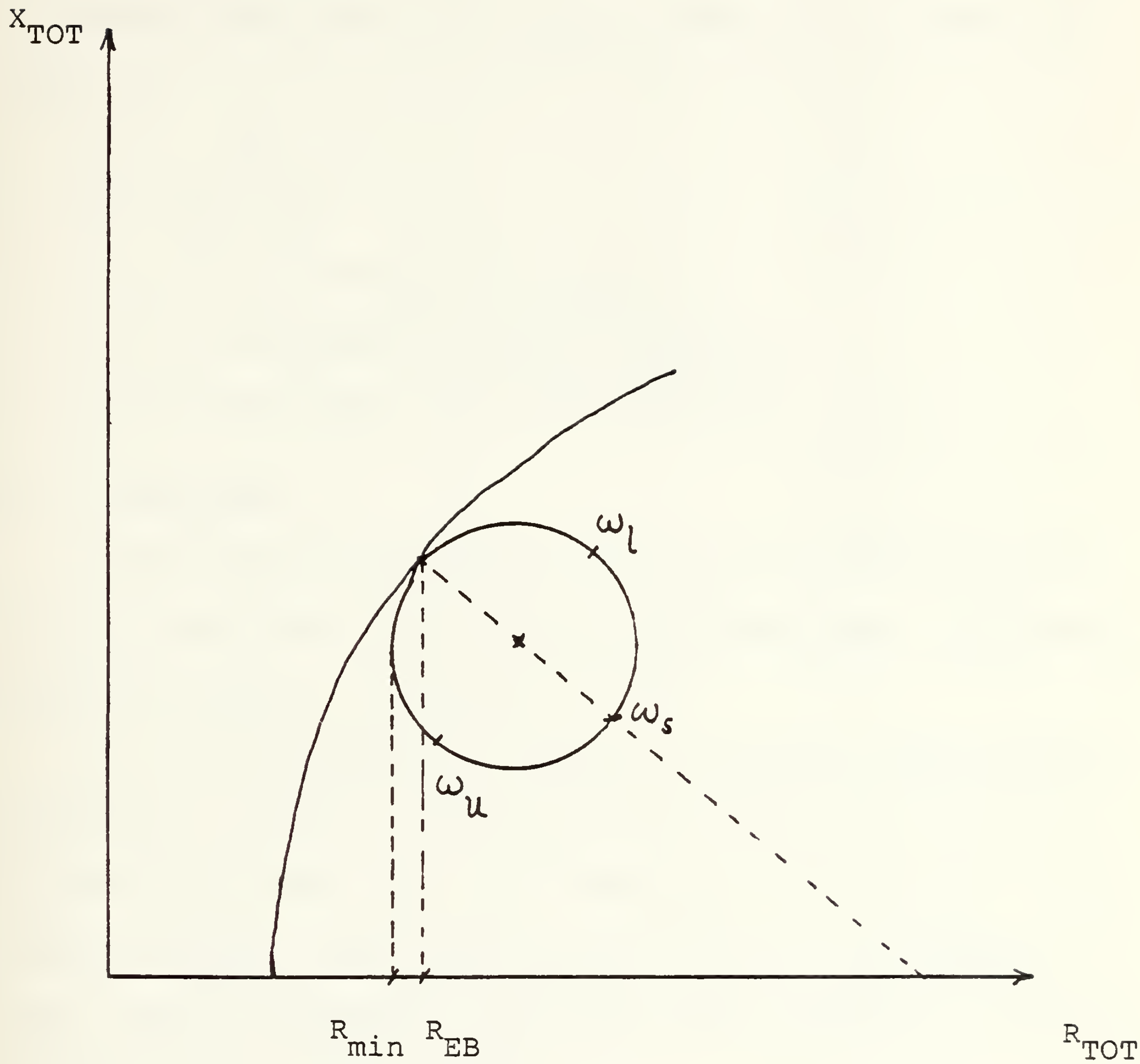


Figure 16. Complex Impedance Plot

G. QUALITY FACTOR Q

Q is a measure of the sharpness of resonance. Also, $Q/2\pi$ is a measure of the ratio of the maximum energy of the driven transducer at its resonance frequency to the energy dissipated per cycle. The quality factor Q is equal to: [Ref. 3]

$$Q = \frac{f_o}{f_u - f_l} \tag{81}$$

f_o is the resonance frequency.

f_u is the upper 1/2 power frequency.

f_l is the lower 1/2 power frequency.

H. EFFICIENCY

Efficiency is the ratio of the output radiated power to the total power delivered to the transducer. Efficiency can be obtained in two ways:

1) By the impedance method: at resonance the motional reactance is zero, and the circuit is reduced as shown in Figure 17 and from which the efficiency is obtained. In a similar manner, from the figure B_E vs. G_E the diameter is known and the radiation resistance when operated in air is assumed to be close to zero:

$$D_W = \frac{\phi^2}{R_m + R_r} \tag{82}$$

$$D_A = \frac{\phi^2}{R_m} \tag{83}$$

Combining equations (77), (82) and (83), one may express the efficiency in terms of the diameter, measured in air and water, and total conductance. [Ref. 3]

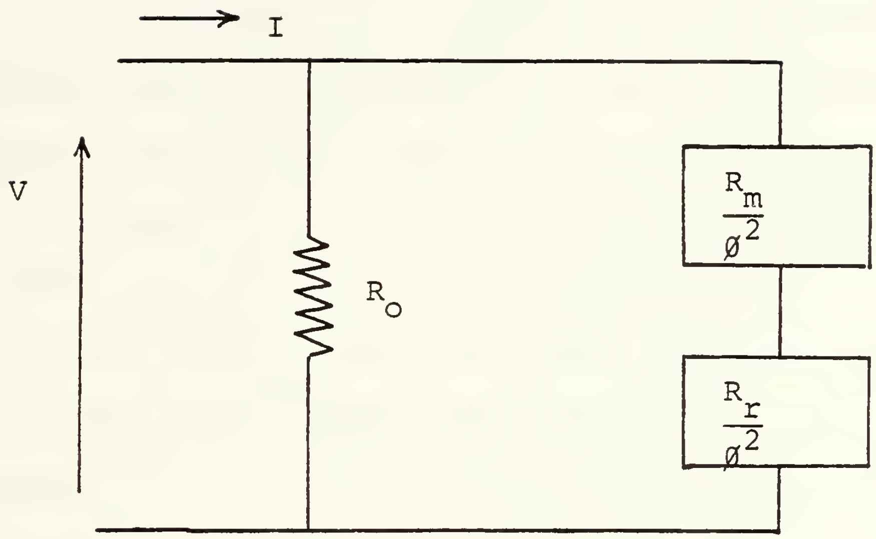


Figure 17. Circuit at Resonance

$$\eta = \frac{D_W (D_A - D_W)}{G \; D_A} \tag{84}$$

In a similar way the efficiency for the magnetic-coupled transducer may be obtained.

$$\eta = \frac{D_W (D_A - D_W)}{R \; D_A} \tag{85}$$

R = total resistance at resonance. This method is prone to many errors because too many assumptions are made. For example, it is assumed that the transducer is completely described by the analog networks and that the impedances are independent of each other. When some transducers are filled with oil one cannot assume that the radiation impedance in air is close to zero.

2) Direct method: the electrical input power and the radiation power are measured, the second is obtained from the sound pressure and the Directivity Factor. The electrical power is

$$P = I^2 R_s = \frac{V^2}{R_p} = VI \cos\theta \tag{86}$$

where θ is the phase angle between V and I and R_s and R_p are series and parallel resistances across the terminals, respectively. [Ref. 1]

$$\text{The power output} = I_{ave} \, 4\pi r^2 = \frac{I_a}{R_\theta} 4\pi r^2 \tag{87}$$

where I_a = intensity measured at some distance r on the axis

But $$I_a = \frac{p_r^{\,2}}{\rho c}$$

$$\therefore \quad P = \frac{p_r \, 4\pi r^2}{\rho c \; R_\theta} \tag{88}$$

The efficiency is then:

$$\eta = \frac{P_a}{P_i} = \frac{4\pi r^2 \, p_r^{\,2}}{R_\theta \, \rho c \, I^2 R_s} \tag{89}$$

If r = 1 meter and the current transmitting response S_I is substituted above, one obtains:

$$\eta = \frac{S_I^{\,2}}{R_\theta \; R_s} \cdot \frac{4\pi}{\rho c} \tag{90}$$

III. MEASUREMENTS PRACTICE

A. SELECTION OF A TESTING SITE

Some general types of available sites are grouped as: [Refs. 1 and 4]

1) The ocean and large lakes.
2) Small lakes.
3) Natural or artificial ponds.
4) Rivers.
5) Anechoic tanks.

Factors that should be considered when choosing a testing site:

a) SIZE: the following parameters should be considered when looking at the size:

1) Reflections from the bottom, surface and boundaries.
2) Homogeneity of the medium, ambient noise, difficulties in the installment of the facility (on shore, floating, rigging, etc.).

b) BOTTOM: it is important to know the type of bottom because it has direct influence of the reflectivity. It could be classified as mud, sand or rock. Soft mud would be more desirable than a hard rock surface. However, mud may contain air or gas bubbles which are very good reflectors. So it would very likely be best to have a fine soft sand bottom.

c) AMBIENT NOISE: it is important to measure the ambient noise level. If it is too high more power will be required

from the transducers to be calibrated. The ambient noise comes from different sources: surface waves, underwater life, shipping, rain, etc.

d) WEATHER: it has importance when the site chosen is the ocean or a lake, since measurements may be possible in fair weather only. Thus, from this point of view the size and geographical location of the site are important. The weather will affect the temperature gradient of the water, the mixing of different waters, and the ambient noise level, which may vary according to the surface wind intensity. If the site is chosen in the ocean, tides and salinity will also play an important role. A homogenous salinity distribution is desired, otherwise it will produce variations in the speed of sound, and hence, variations in the reciprocity parameter, J. Tides play an important role too. The geographical location of the sites should be in latitudes where tide amplitudes are small in order to avoid relative movements of transducers and flow noise, due to currents produced by the tides.

If the chosen testing site is an anechoic pool in the open the rate of evaporation of the water has to be considered if a constant water level is desired. The rate of evaporation depends on temperature and wind, the latter being the more significant factor. To prevent this a thin plastic sheet could be floated on the surface. It is necessary also to have a circulating pump with chlorine injection system to remove the thermocline and control the algae. To prevent the aggravation of corrosion of the metals due to chlorine gas, caustic soda has to be added to the water to keep the pH at about 7.4.

e) LOCATION OF THE TEST EQUIPMENT AND RIGGING: it is convenient to have the transducers to be calibrated hanging from a rigid structure and the amplifiers and measuring equipment as close as possible to the elements being tested. The rigging has to be strongly built to support the heavy transducers of low frequency sonars presently used (SQS-23, about 10 tons; SQS-26 about 20 tons).

B. PREPARATION

1) Transducers should be washed with a wetting agent to remove the surface oil film before immersing them in water. By doing so, no bubbles will attach to the transducers, and a good transducer surface to water impedance match will be obtained. The surfaces should be inspected during the course of the measurements to ensure that bubbles have not formed on the surfaces.

2) Transducers should be at the same temperature as the medium surrounding them, therefore, they should be immersed some time before the calibration begins.

3) The rigging should be as acoustically invisible as possible. Any air space will cause strong reflections. Rigid structures must be built in such a way that no vibrations are transmitted to the transducers involved in the calibration.

4) POSITIONAL REQUIREMENTS:

a) Both projector and receiver should be at the same depth.

b) The separation between them should be known.

c) The direction at which the acoustical axis points, should be known.

d) If the projector or receiver are going to be rotated, the direction at which their acoustical axis is pointing, should be known.

e) If one of the transducers' real acoustical centers does not coincide with the chosen acoustical center, their separation has to be at least 100 times the separation distance between the two centers.

ERRORS (Fig. 18): If a projector and hydrophone are positioned with an error of two percent, for example, it would cause an error of less than 0.2 dB in pressure level. If the hydrophone is not on the axis of the projector, it can result in an error of several decibels in pressure level. Therefore, it is good practice to orient the transducers acoustically for maximum output response.

C. FREQUENCY RANGE OF THE TANK

The tank size needed is a function of the wavelength of the acoustic signal. What should be considered is the distance from the nearest boundary to the path of projector-hydrophone. To determine the tank size, the following factors should be taken into account:

1) Whether the nearest boundary is parallel or perpendicular to the path.

2) The absorption at the walls is a consequence of the rapid decay of the reverberation between the pulses and it is more effective at low frequencies.

When using pulsed-sound, the signal coming from the direct path should arrive completely before the reflected wave

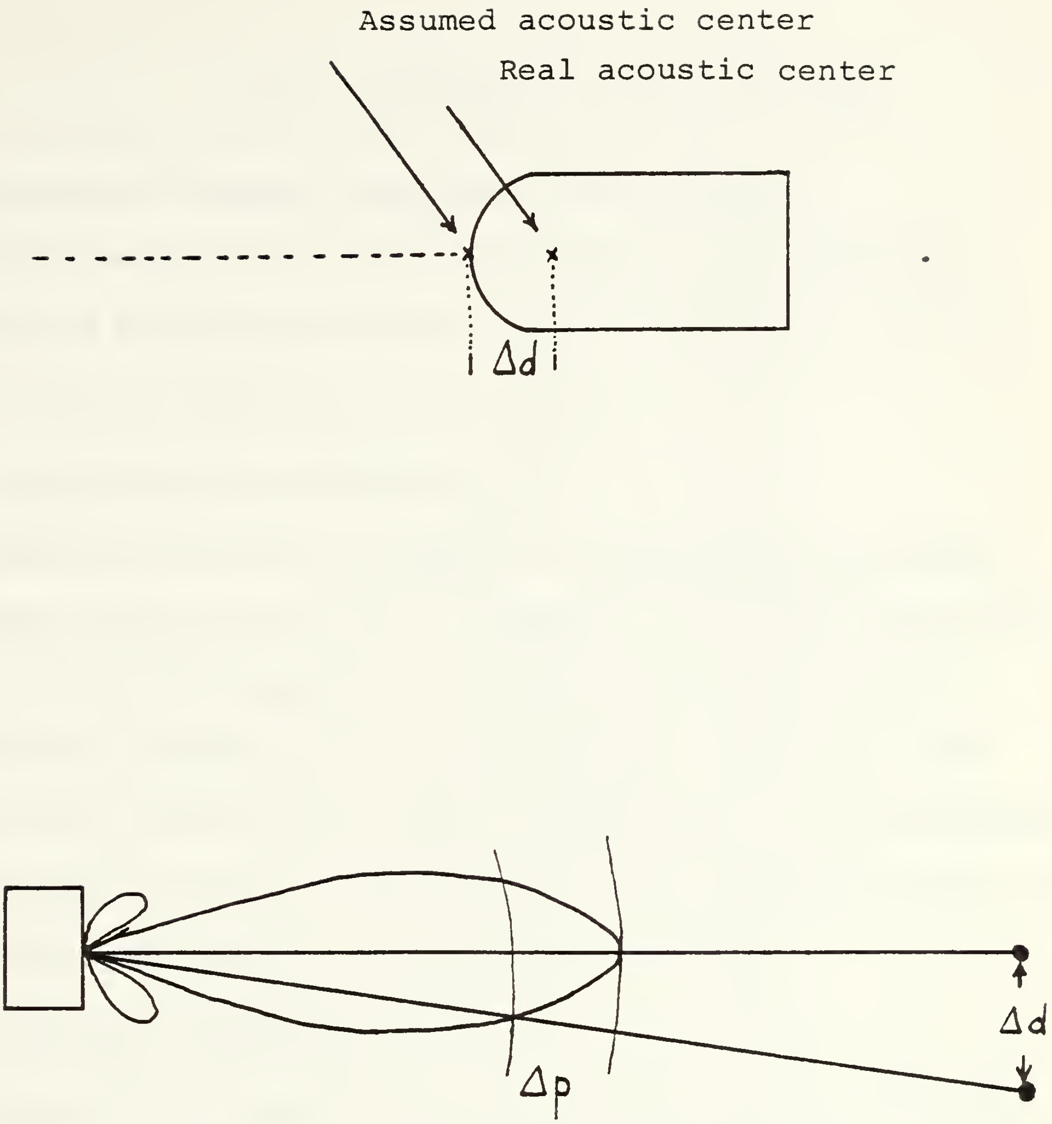


Figure 18. Possible Error Sources

begins to arrive. The minimum path difference is T seconds or $c \cdot T$ meters. The minimum tank length L and minimum width is:

$$L = d + cT \tag{91}$$

$$W = [(d + cT)^2 - d^2]^{1/2} = (2dcT + c^2T^2)^{1/2} \tag{92}$$

d = separation between hydrophone and projector.

The equation can be put in terms of the transducer parameter Q and the wavelength lambda, taking into account the proximity criteria.

D. ELIMINATION OF REFLECTIONS

Reflections from the surface, bottom, walls and from any other body in the water interfere in the sense that they distort the plane progressive sound wave required for a calibration. Usually all tanks are small, therefore the pulsed sound technique is used to eliminate the interferences coming from the walls. To attenuate the reflections the tanks are coated with acoustic absorbing materials.

E. PROXIMITY CRITERION

Ideally, the hydrophones should be placed at a distance from the source beyond that at which the Fresnel zone, or near-field, ends and into the range at which Fraunhofer zone or spherically divergent, far-field zone begins. This distance is variable depending upon the type and size of the projector and the frequency being used. The standard for a uniform circular piston is: [Refs. 1 and 5]

$$X \geqslant \frac{\pi a^2}{\lambda} = \frac{area}{\lambda} \tag{93}$$

$$X \gg a$$

To find a criterion for other than a uniform piston (for example: shaded or tapered) can be very difficult if they are not an easy geometrical shape like a square, circle or a line. Examples of criteria:

Square pistons:
$$X \geqslant \frac{W^2}{\lambda} \tag{94}$$

$$X \gg W$$

Polygons can be approximated to a square or circle:

$$X \geqslant \frac{area}{\lambda} \tag{95}$$

Line or thin cylinders:
$$X \geqslant \frac{L^2}{\lambda} \tag{96}$$

$$X \gg L$$

F. PULSED SOUND

If the effects of interference from the boundaries, standing waves and electric crosstalk have to be eliminated, the pulsed sound technique has to be used. Electric cross-talk is an electric or electromagnetic signal that unintentionally is transmitted directly from the transmitting equipment to the receiving equipment, by-passing the acoustic path. The pulsed sound is a pulse-type signal, which consists of a limited number of wave cycles and is transmitted by the projector. The projector and receiver (hydrophone) are controlled by a time gating process such that the receiver

receives only during the period of time at which the direct-path pulse is arriving at the hydrophone. Before and after this short period of time the hydrophone does not receive. By doing this, one eliminates the signals before the pulse which can be due to transients of the beginning of the signal and crosstalk and after the pulse, which can be due to the reflections from the boundaries. The pulses can be formed by modulating a sine wave with a square-wave. Since many projectors are resonant, it may take some time for the projector to reach steady state output after it is turned on. After shutting it off, it keeps on oscillating at its resonance frequency. The receiving gating time of the hydrophone may be set, shorter than that of the projector's because it is desired to pick up only the steady state part of the pulse generated by the projector. The pulse duration should be long enough to reach steady state. It takes a number of cycles, approximately equal to the value of the Q, to reach the steady state during which energy is being stored in the system. After the pulse has reached its steady state it should last sufficiently long so that the receiver reaches its steady state condition. When the signal is shut off, the system rings at its resonance frequency and will take approximately Q cycles to die out exponentially. Pulsing has a low frequency limit depending on the quality of the equipment, the geometry of the tank, and the differences in distance between the direct path and the shortest interference path. [Ref. 1]

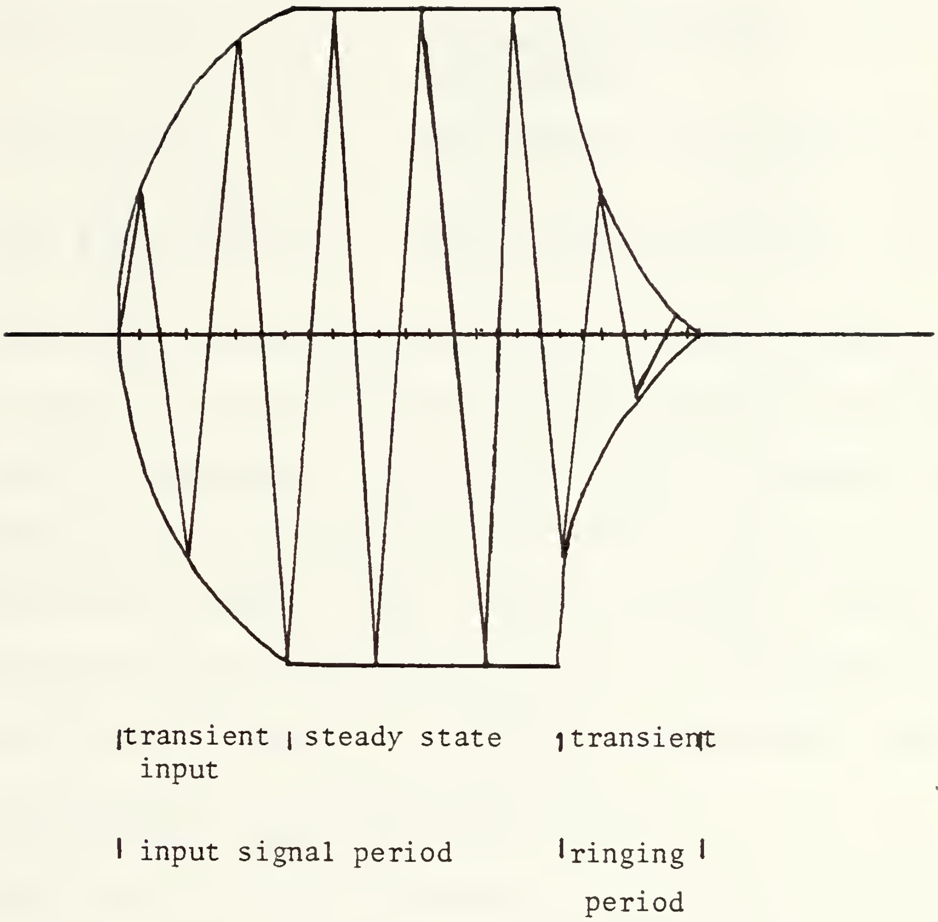


Figure 19. Pulse in a System

G. PULSE DURATION (T)

Figure 20 shows a water tank of dimensions h·L·b with a projector and a hydrophone. It can be seen that the pulse length should be short enough so that measurements are not disturbed by reflected pulses (echos) arriving at the receiver before the termination of the direct signal. This sets the following limitations to the pulse duration.

$$T \leq 2\frac{d}{c} \qquad \text{reflections between transducers} \qquad (97)$$

$$T \leq \frac{L-d}{c} \qquad \text{reflections from the walls} \qquad (98)$$

$$T \leq \frac{\sqrt{h^2+d^2}-d}{c} \qquad \text{reflections from upper and bottom surface} \qquad (99)$$

The pulse length would also be governed by the low frequency limit. The pulse length is determined by the requirement $T > 1/f$. Example: if the low limit of interest is 1 kHz, then T should be greater than one wave period or one thousandth of a second. The minimum number of cycles in a pulse depends on the sophistication of the equipment and the ability of the equipment to respond to transients. [Ref. 1]

H. INTERFERENCE FROM BOUNDARIES

These are the wave interference and the Lloyd's mirror effect caused by the path differences. It can be identified by its regular amplitude variation at regular frequency differences. (Fig. 21) This frequency difference can be used to determine kind of interference which is taking place.

$$\Delta x = \frac{c}{\Delta f} \qquad (100)$$

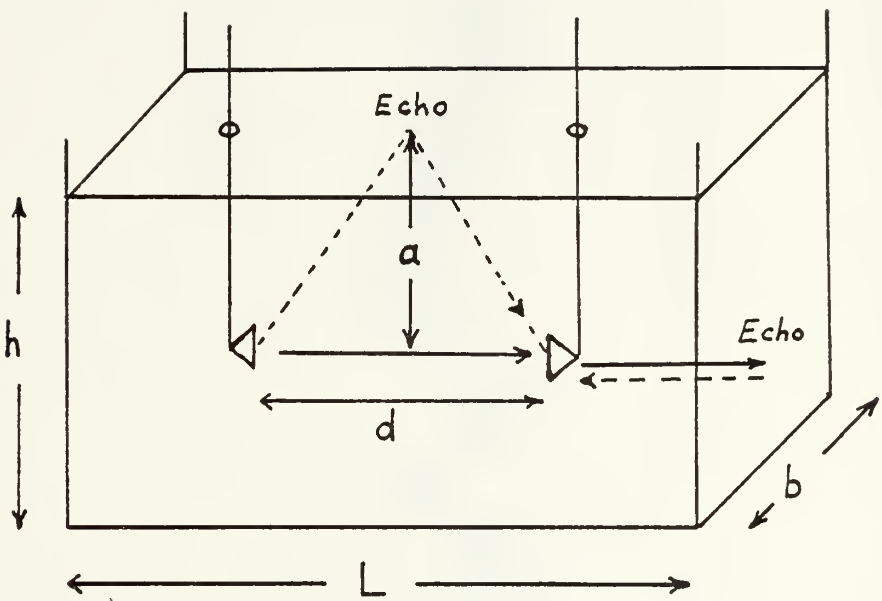


Figure 20. Direct and Reflected Signals in a Tank

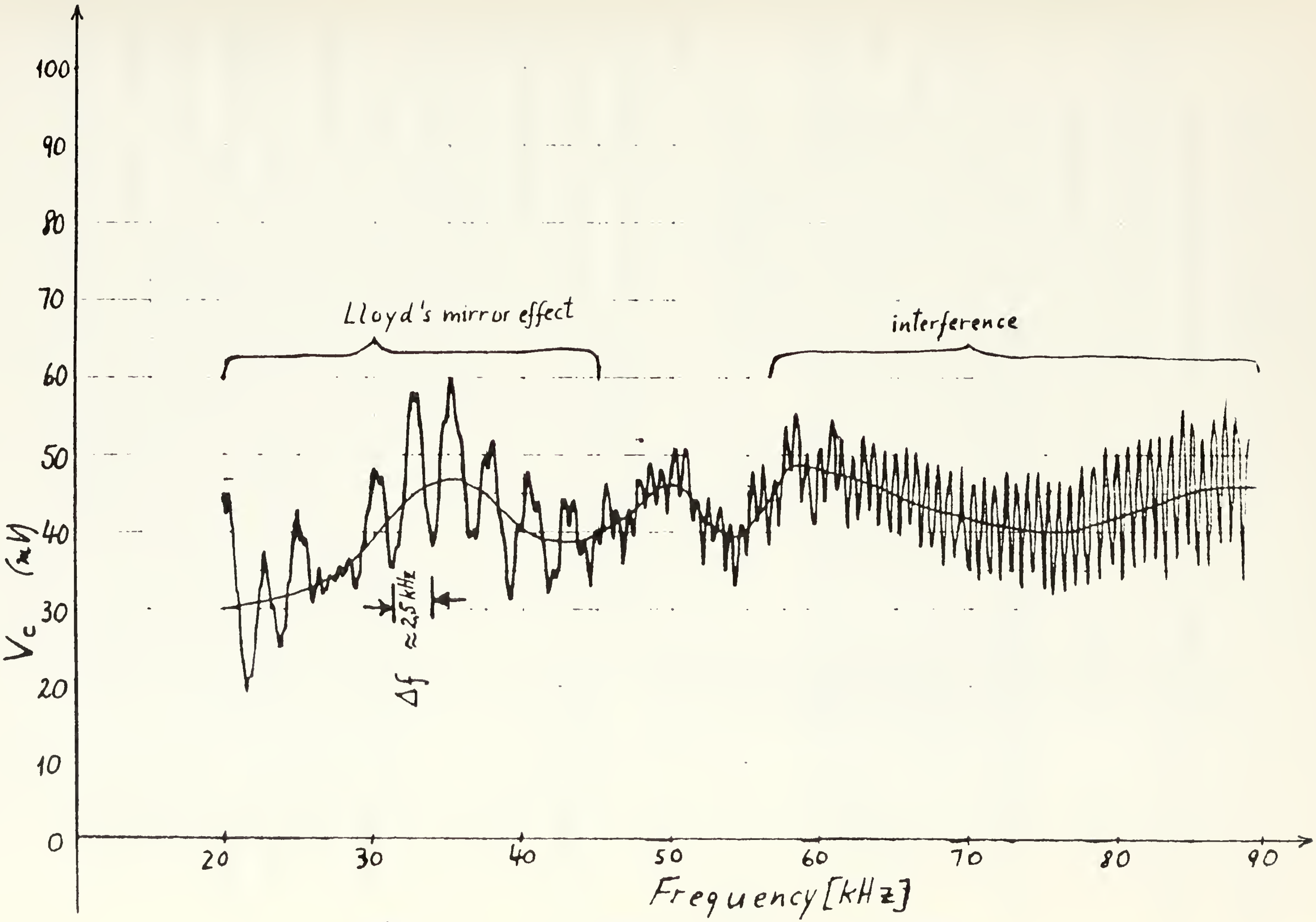


Figure 21. Interference Observed in Calibration

And from the geometry in Figure 20:

$$\Delta x = 2\left[a^2 + \left(\frac{d}{2}\right)^2\right] - d \tag{101}$$

Interference can be eliminated by the pulsing technique, described earlier.

I. CAVITATION

If a sonar transducer must be inspected while operating at full power output, special care has to be taken to not surpass a certain value called cavitation threshold. The cavitation threshold can be expressed as a peak pressure in atmospheres or as a plane-wave intensity in watts/cm^2:

$$I_c = \frac{(.707\ 10^6\ p_c)^2}{\rho\ c} = .3\, p_c^2 \tag{102}$$

where

I_c is the cavitation threshold intensity

p_c is the peak pressure of the sound wave causing cavitation in atmospheres

ρ is the density in gr/cm

c is the speed of sound in cm/sec

When the cavitation threshold is multiplied by the projector's face area (in cm^2) the maximum output mechanical power allowable (in watts) radiated is obtained before cavitation occurs. Beyond that limit there is a loss of acoustic power due to absorption and scattering by the cavitation bubbles, change of the beam pattern of the projector and of the acoustic impedance of the medium.

In a practical way, the cavitation threshold may be found by plotting source level in decibels versus the driving voltage level in decibels (20log V). At the point where the curve begins to lose its linearity, the cavitation threshold is said to be reached.

The cavitation threshold may be raised by

1) Increasing the frequency.

2) Decreasing the pulse duration.

3) Increasing the depth or hydrostatic pressure.

These factors have a direct influence on the procedure of choosing a calibration site and/or designing an anechoic tank. [Ref. 2]

J. ABOUT ANECHOIC TANKS AND ABSORBERS

A prerequisite for conducting underwater laboratory experiments with acoustic sources having wide radiation patterns is an anechoic tank. Such tanks have been in use for some time at the lower ultrasonic frequencies where wide radiation patterns are characteristic of some kinds of sources. At higher frequencies the radiation patterns are narrower and the use of pulse techniques has made the need of anechoic tanks less pronounced. Now with the new hydrophones that have wide radiation patterns in the megahertz region, high frequency anechoic tanks have become a practical necessity.

In order to perform measurements without undesirable reflections from the boundaries, it is necessary to make the walls of the tank, as well as its bottom and surface,

reflectionless. To achieve this, one needs a broad-band absorber consistent with the dimensions of the tank, which causes sufficiently small reflections in the frequency range to be used.

The following list gives a brief description of some of the linings that have been used for anechoic tanks:

1) Mason lining: close-packed metal mesh or screening immersed in Castor oil and separated from the water by rho-c rubber sheeting.

2) "Fafnir" (English and German design): anechoic array of lossy rubber wedges containing air cavities that decrease the stiffness of the rubber.

3) "Alberich" (German design): a layer of lossy rubber, less than a wave-length thick, containing resonant cavities of air where the size of the cavity is controlled.

4) Insulkrete: anechoic array of porous wedges made from pine sawdust and Portland cement.

5) Butyl rubber lining: provides satisfactory absorption in the megacycle region.

6) Saper D: it is a modification of the German World War II absorber called "Alberich," that can operate up to a depth of 675 ft. Its technical data is classified.

7) Saper T: this is specially designed for anechoic tank lining applications. It provides 10 dB echo reduction down to frequencies as low as 500 Hz.

The absorbing properties of the underwater linings are the result of one or more of the three modes of dissipation: flow viscosity, anelasticity of the material and absorption

by air bubbles. Of the linings listed (1) and (4) correspond to the flow viscosity type and the rest correspond to the anelastic properties of rubber type materials. The last two are manufactured by B. F. Goodrich.

1. <u>Acoustic Impedance of Linings</u>

The impedance concepts are used to analyze the reflecting properties of the linings. Consider a slab of lining in contact with the steel tank wall and irradiated by a normal incidence plane wave. A small reflection factor, ratio of reflected to incident amplitude, can be obtained at some frequencies, depending on the thickness of the lining. At other frequencies it can be larger ($>$ 0.1) and have such a large number that the lining would not be efficient anymore. Linings that behave like those described above and which are thin compared to a wavelength and have a small absorption coefficient, belong to the Alberich type.

On the other hand, if the lining thickness and absorption coefficient are sufficiently large, the lining behaves as an infinitely thick medium. Undesirable reflection will still exist at the front face of the lining if there is a mismatch of the characteristic impedance of the lining and water. To diminish this mismatch cones or wedges are attached to the lining in order to create a transition region where the impedance changes gradually. "Fafnir" and Insulkrete belong to this type of lining. The frequency range at which this type is effective depends upon the spacing and size of the wedges and cones.

2. Air Bubble Linings

Bubble screens, formed by distributions of air bubbles in water, are effective in reducing reflectivity at some frequencies because individual bubbles not only scatter sound diffusely, but they also absorb it.

The linings that use this method contain bubbles that are spatially fixed by a thin latex coating of individual horsehairs or they can be fixed by another method.

3. Impedance Matching

A sound-coupling medium is necessary to transmit energy from the active element into the water, when an acoustic window is not directly coupled with the active face.

Criteria for the selection of the acoustic coupler liquid: four categories of properties do exist for comparison of their capabilities: acoustical, chemical, physical and environmental.

a) Acoustical properties: the velocity of sound in the liquid should be close to that of water so that refractive effects, such as convergence or divergence, do not take place. The acoustical impedance, Rho-c, should match with that of water to prevent reflections at the window interface. At higher frequencies the dissipation factor of the liquid and loss of signal should be considered.

b) Chemical properties: all air and moisture is extracted from the transducer, then it is filled with the liquid. The liquid should be stable for a long time under various temperatures, pressures and vacuum. It should not react with other materials and should not be a catalyst. If water diffuses into the transducer it should be absorbed by it without changing its characteristics.

c) Physical properties: the characteristics and behavior of the liquid should be known: viscosity compatible with filling operations, temperature over the range of exposure, change of volume and/or pressure, dielectric and volume resistivity, adhesion and cohesion under high intensity acoustic field, and in the presence of an electric arc-over.

d) Environmental properties: should be inert in the sense that it will not injure nor intoxicate, with its vapors, the people repairing or constructing transducers.

From all the acoustic liquids studied by the Navy it is most recommended that polyalkylene glycol be used for sonar transducers. [Refs. 11, 12, 13, 17 and 18]

IV. INSTRUMENTATION

The electrical measurements required for obtaining the hydrophone sensitivity can be done at two different distances, usually 1 or 2 meters. If the measured loss agrees with the theoretical, one can assume that the following conditions are satisfied:

1) The hydrophone is in the far-field of the projector.
2) The acoustic centers have been properly chosen.
3) The hydrophone is linear.
4) There are no reflections or electrical crosstalk.

On the other hand, if this test fails, one or more of these conditions are not satisfied.

In some facilities where a lot of testing is done and when time is an important factor, automated instrumentation procedures are used. For example, the oscillator sweeps automatically over the frequency range of interest, the signal is automatically filtered and recorded.

A. SENSITIVITY, FREQUENCY RESPONSE

The gating system shown in Figure 23 has two main functions: to gate a continuous sine wave signal in order to obtain a tone burst to drive the transmitter and to gate the received signal, slightly delayed, and detect the peak value. The delay in the receiving gate is introduced because of the transmission delay for sound in water, and the peak detection is chosen because of the tone burst technique. The

gate width (pulse length), the tone burst repetition frequency and the delay between the output signal and the measuring gate can all be adjusted to suit the requirements governed by water tank dimensions, measuring frequency, distance between transducers, etc.

The Power Amplifier has to be able to drive a piezoelectric transducer. This is due to the fact that the amplifier has to work into a capacitive load where all the power is reflected. At the same time, the constant driving current must be high in order to obtain a sufficiently large signal-to-noise ratio at low frequencies which requires a high voltage at high frequencies. If a transducer has to be driven hard, a perfect impedance matching is required.

The sensitivity and frequency response of a hydrophone, used either as a transmitter or receiver, can be found with the set-up shown in the next figure. The oscillator provides a swept sine signal in synchronism with frequency calibrated paper on the X-Y recorder whereby the response curve is recorded automatically.

For self-reciprocity calibration the same set-up may be used. The reciprocal transducer must be pointed to the air-water surface. The preamplifier has to be connected to the same transducer and the gating circuit has to switch on and off the receiving and transmitting circuit, respectively, when operating as a hydrophone and vice-versa when operating as a projector.

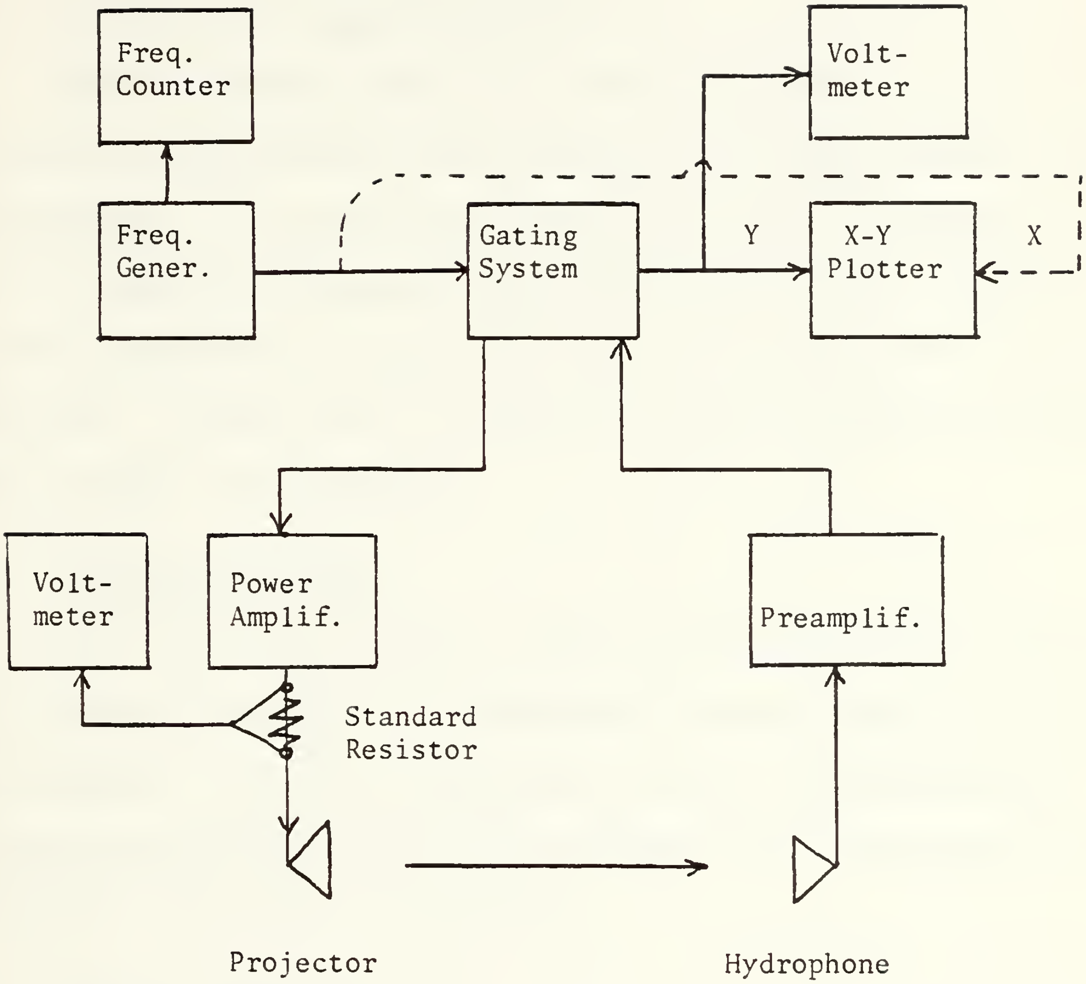


Figure 22. Instrument Arrangement for Obtaining Sensitivity

For the comparison method, again the same set-up can be used. It is convenient to plot on the X-Y plotter the open circuit output voltages of the known and unknown hydrophones versus frequency. [Refs. 14, 15 and 16]

B. DIRECTIONAL CHARACTERISTICS

The following, Figure 23, shows a suitable set-up for recording directional characteristics of both receiver and transmitter. In this set-up the oscillator is manually tuned to the desired frequency while the turntable rotates the tested transducer or hydrophone in synchronism with the X-Y plotter. In this case it would be very convenient to have a polar paper level plotter.

C. IMPEDANCE METHOD

With the configuration shown in Figure 24 the admittance $|y|$ versus frequency or impedance $|z|$ versus frequency can be plotted. It is also possible to plot the conductance versus susceptance using the frequency as a parameter and the impedance loop will be obtained.

D. QUALITY FACTOR Q

As explained before, the Q of the transducer can be obtained from the complex impedance or admittance plot. Another way to do it is to use the equipment configuration required to obtain the sensitivity response. Reading the frequency for which one obtains a peak in the dB scale of the voltmeter and the frequencies for which one reads 3 decibels down from the peak and using formula (81) the quality factor Q is easily calculated.

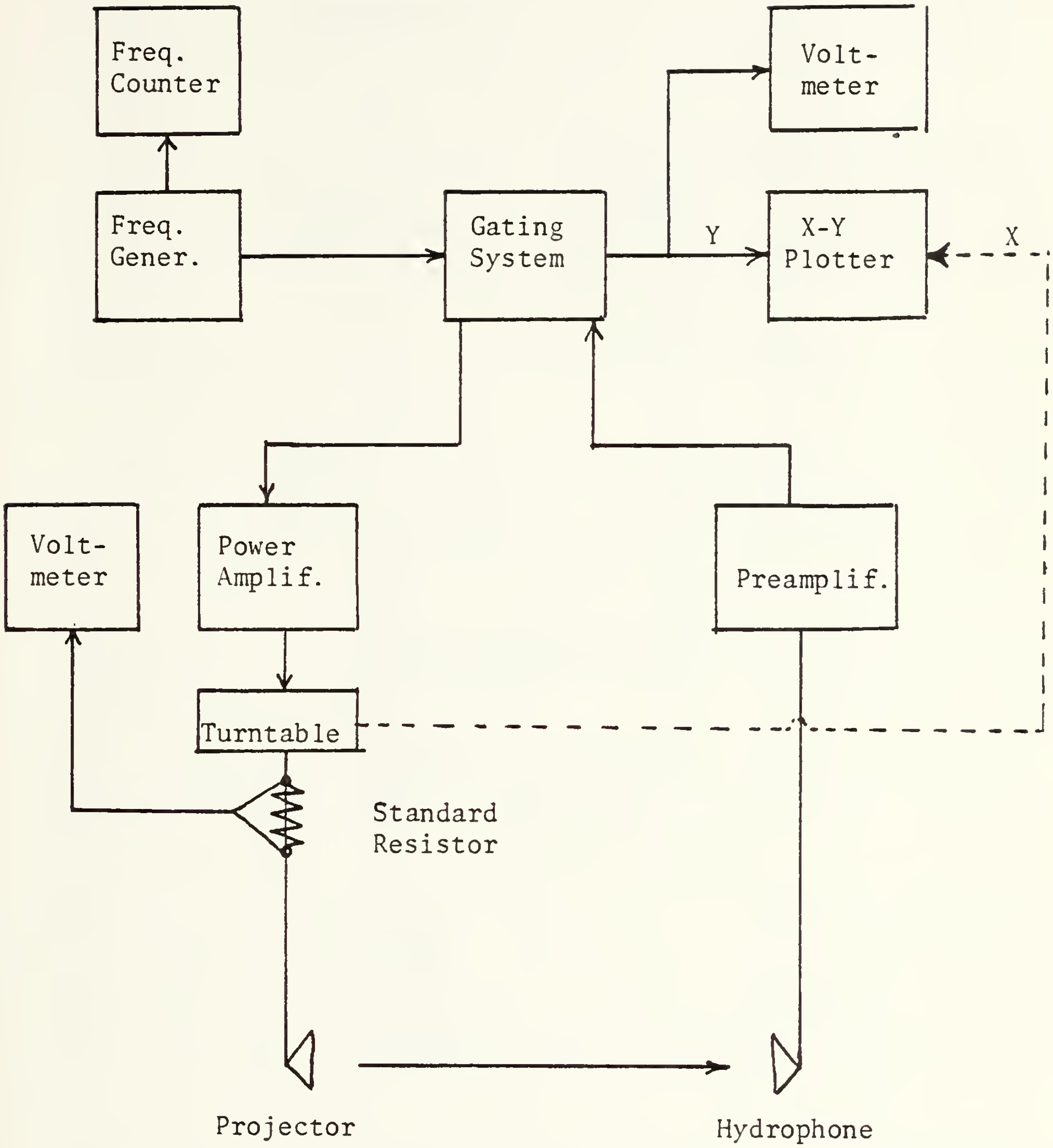


Figure 23. Instrument Arrangement for Obtaining the Directional Characteristics

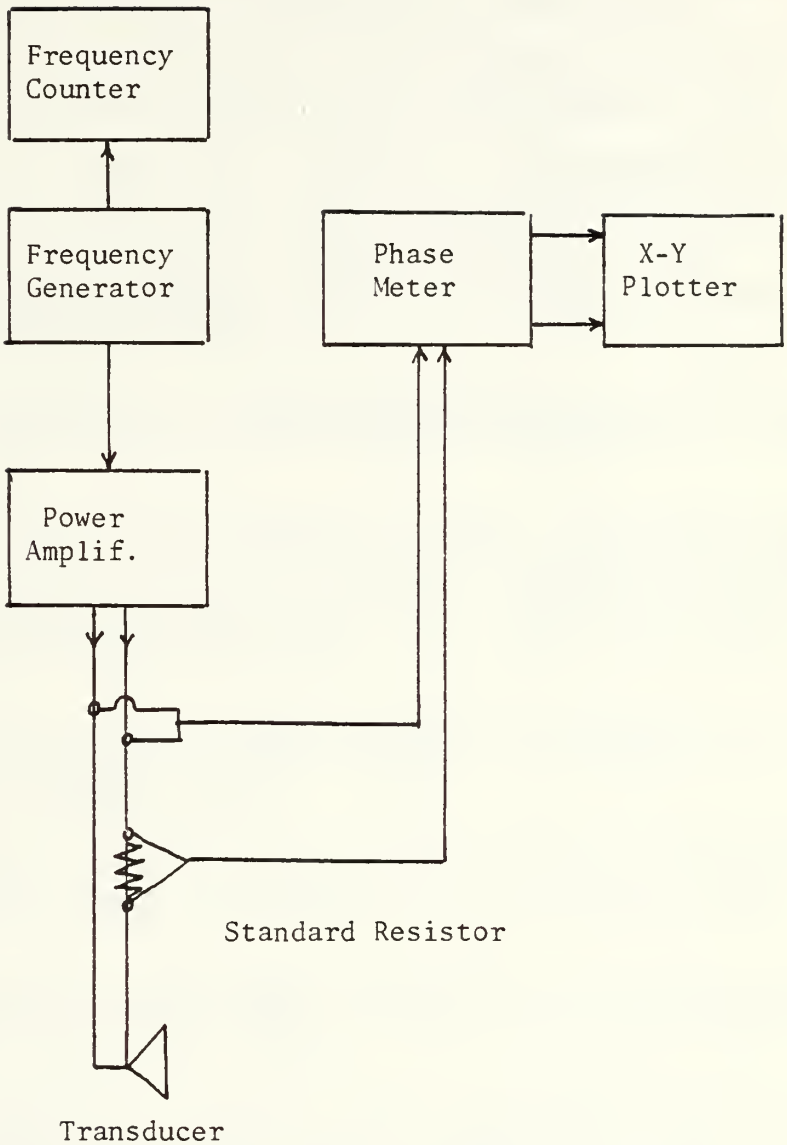


Figure 24. Instrument Arrangement for Obtaining Impedance Measurements

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